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THE MEASUREMENT OF AIR QUANTITIES AND ENERGY LOSSES IN MINE ENTRIES

BY

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AND

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ILLINOIS COAL MINING INVESTIGATIONS COÖPERATIVE AGREEMENT

(THIS REPORT WAS PREPARED UNDER A COÖPERATIVE AGREEMENT BETWEEN THE ENGINEERING EXPERIMENT STATION OF THE UNIVERSITY OF ILLINOIS AND THE ILLINOIS STATE GEOLOGICAL SURVEY)

BULLETIN NO. 158

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The management of the Engineering Experiment Station is vested in an Executive Staff composed of the Director and his Assistant, the Heads of the several Departments in the College of Engineering, and the Professor of Industrial Chemistry. This Staff is responsible for the establishment of general policies governing the work of the Station, including the approval of material for publication. All members of the teaching staff of the College are encouraged to engage in scientific research, either directly or in coöperation with the Research Corps composed of full-time research assistants, research graduate assistants, and special investigators.

The volume and number at the top of the front cover page are merely arbitrary numbers and refer to the general publications of the University of Illinois; *either above the title or below the seal is given the number of the Engineering Experiment Station bulletin or circular which should be used in referring to these publications.*

The present bulletin is issued under a coöperative agreement between the Engineering Experiment Station of the University of Illinois, the State Geological Survey. The reports of this coöperative investigation are issued in the form of bulletins by the Engineering Experiment Station, the State Geological Survey, and the United States Bureau of Mines. For bulletins issued by the Engineering Experiment Station, address Engineering Experiment Station, Urbana, Illinois; for those issued by the State Geological Survey, address State Geological Survey, Urbana, Illinois; and for those issued by the United States Bureau of Mines, address the Director, United States Bureau of Mines, Washington, D. C.

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THE MEASUREMENT OF AIR QUANTITIES AND ENERGY LOSSES IN MINE ENTRIES

I. Introduction

1. *Object and Scope of Investigation.*—The ventilation of coal mines is one of the most essential operations in connection with mining work. Legal requirements set minimum standards for the amount of air that must be supplied to the mine, but the occurrence of explosive gas, methane, in many cases demands quantities of air that are greatly in excess of the minimum legal standards. The importance of ventilation with respect to safety cannot be over-emphasized. With the increase in the size of modern mines and the very gassy condition of some of them the problem of handling large volumes of air in the mine so as to have efficient and safe ventilation at reasonable cost becomes increasingly difficult.

In view of the great importance of mine ventilation it is strange that so little work has been done in determining the laws governing the flow of air in mines. The Atkinson formula,* $R = ksv^2$, proposed in 1854, stated that the mine resistance, or the total resistance to flow, varied directly as the rubbing surface and the square of the velocity. This formula has the merit of simplicity and has been considered satisfactory for most uses. Atkinson's value of 0.0 000 000 217 for k has long been known to be too large, but it has continued to be used because of its being "on the safe side."

Within the last three or four years the U. S. Bureau of Mines has carried on some investigations at its Experimental Mine at Bruceton, Pennsylvania, and in metal mines at Butte, Montana, in coöperation with the Anaconda Copper Mining Company. The complete results of this work have not been published, but brief summaries have been issued as Reports of Investigations, Serials 2621, 2647, 2663, and 2671. Important information has been obtained in these investigations regarding coefficients of friction and certain features of air flow. The quantity of air was measured by pitot-tube traversing at a specially-constructed air-measuring station, and a study of the results obtained indicates a high degree of accuracy.

In planning a program of ventilation research at operating coal mines in Illinois, the authors considered, in view of the different losses to be studied that were functions of the velocity of the air current, that

*See p. 60.

it was important to try to develop a method of measuring air flow that would not require the construction of a special measuring station, and yet would give results with a reasonable degree of accuracy. The building of special air-measuring stations at operating mines involves considerable expense; they cannot be located on haulage roads, and the results obtained lose their accuracy within a relatively short distance due to air leakages through stoppings. Extended work would require the erection of a measuring station at every point where air quantities had to be determined—a prohibitive expense.

The primary object of these investigations was, therefore, to see whether pitot-tube traversing methods could be applied with reasonable accuracy at *any* desired location without building a measuring station and without special preparation of the section. As a secondary feature it was planned to secure pressure-loss data in conjunction with the velocity measurements in order to obtain information on the magnitude of so-called "friction" losses, as well as of the losses due to splitting, special resistances, etc.

2. *Acknowledgments.*—The work described in this bulletin was done under the direction of the senior author. The field work was done by the junior author and by Prof. A. J. Hoskin, Research Associate Professor of Mining Engineering. Mr. N. A. Tolch, Research Assistant in the Engineering Experiment Station, assisted in later field work as well as with the computations.

Special mention should be made of the courtesy of Dr. L. E. Young, General Manager, and Mr. I. N. Bayless, Mine Superintendent of the Union Colliery Company, in permitting these experiments to be carried on at the Kathleen mine, Dowell, Illinois.

II. Apparatus Used

3. *Anemometer and Gages.*—Three instruments, the anemometer, the Ellison gage, and the Wahlen gage, with suitable accessory apparatus, were used directly in studying air flow.

The anemometer was a Davis instrument, 4 inches in diameter, registering to one foot.

The Ellison gage used is in reality four separate gages mounted, one directly below another, in one frame. For purposes of reference they are designated A, B, C, D, from top to bottom. They are alike in construction, each having a high-pressure and a low-pressure connection nipple at the top of the frame. The scales are about 10 inches long on a slope of 1:10, and are graduated to read directly to 0.01 in. of water. The liquid used is a special Ellison inclined draft gage oil, red in color, provided by the manufacturer. It has a specific gravity of about 0.835 at 60 deg. F. The gage is shown in Fig. 1.

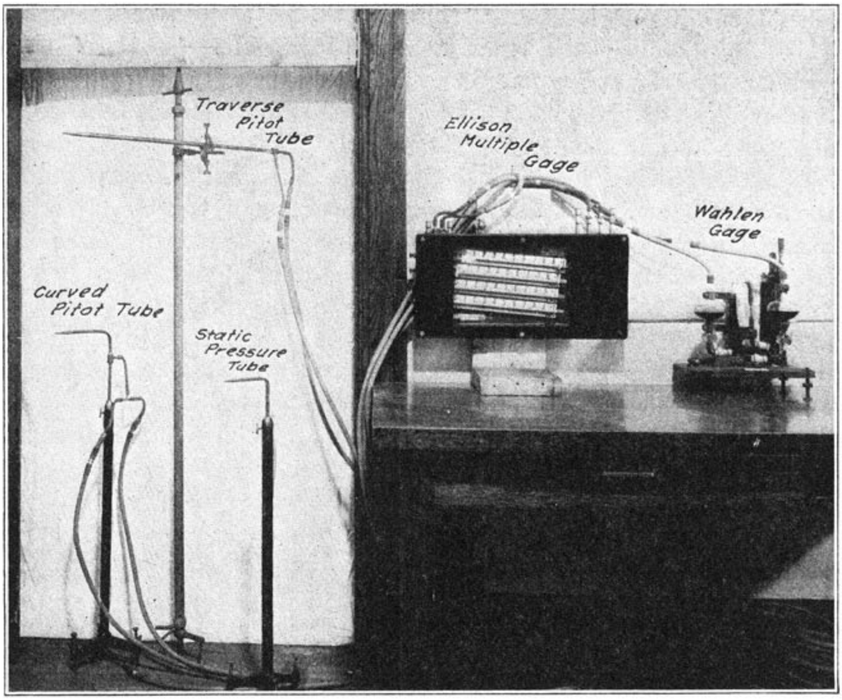

FIG. 1. EQUIPMENT FOR PRESSURE DETERMINATION

The Wahlen gage* is also pictured in Fig. 1. It consists of two bulbs of relatively large cross-sectional area connected to each other by an inverted U-tube which rises above both bulbs. One arm of the U-tube is constricted to a very small cross-section at the level of the maximum diameter of the bulbs, and is marked with an index line at this datum. The bulbs are mounted on a heavy metal base provided with leveling screws and spirit levels. One of the bulbs is fixed on the base while the other is supported on a carriage which permits of vertical motion through a range of an inch or a little more. Its position can be regulated by either of two screws, one a graduated micrometer for

*For a complete description of the Wahlen gage see "Investigation of Warm-air Furnaces and Heating Systems," Univ. of Ill. Eng. Exp. Sta. Bul. 120, pp. 92-98.

pressure readings, and one not graduated, for setting the index reading at zero. The micrometer is a standard precision micrometer with the head reading direct to 0.001 in.

When ready for use both bulbs are filled to their maximum diameter with a colored alcohol solution which has been saturated with the kerosene-ligroin mixture used in the upper part of the inverted U-tube. This latter liquid is adjusted in density by changing the relative proportions of its components until it is just a little lighter than the alcohol. It is colorless, and when admitted into the U-tube, which is completely filled with it, it remains above the alcohol. The meniscus between the two liquids is distinct, due to the different colors, red below and white above. The meniscus adjacent to the movable bulb is kept within the constricted portion of the U-tube and is used as the index meniscus by bringing it to the index line at each reading.

An index, or "zero," reading is taken by connecting the two bulbs to each other, thus preventing differential pressures between them, and opening the stop-cock, having the instrument leveled, of course. This permits the surface of the alcohol in the two bulbs to come to the same level. With the micrometer set at zero the meniscus is brought to the index line by raising or lowering the movable bulb, using the non-graduated screw. Such a movement has the effect of changing the liquid levels with respect to the bulbs, and of causing the meniscus to move with very great rapidity with respect to changes in the bulbs, due to the relatively small cross-sectional area at the index line. If preferred, the gage may not be set to zero for an index reading but may be brought to adjustment with the micrometer screw and a reading as of zero pressure taken on the micrometer. This was the method followed in most of this work.

Pressure readings differ in principle from index readings only in that the two bulbs are under a differential pressure which causes a change in level between the liquid surfaces in the two bulbs equal to the difference in pressure measured as a head of the alcohol which is contained in the gage. As long as the pressures remain constant and the system is left open the two liquids will retain this difference in level, which is measured by moving one bulb vertically until the liquid surface in the other has returned to its index position. The amount of movement required is a direct measure of the pressure differential, and is read on the micrometer in inches of alcohol.

The movable bulb is connected to the higher pressure and the fixed bulb to the lower pressure. With the stop-cock opened this has the effect of lowering the surface of the alcohol in the movable bulb, of raising it in the fixed bulb, and of raising the meniscus above the index line. As the movable bulb is lowered with the micrometer, the meniscus falls with it and is brought to the index line. This is an adjustment which can be gaged quite accurately and is a very sensitive one, a vertical movement of the liquid in the bulbs resulting in a movement of the meniscus more than 100 times as great.

4. *Gage Corrections.*—Since the Wahlen gage readings are in inches of alcohol each must be converted to inches of water by multiplying it by the specific gravity of the alcohol. This factor was determined at three different temperatures with a Westphal balance, and the results plotted and connected with a straight line as shown in Fig. 2. From this curve the specific gravity corresponding to the gage temperature at the time of observation can be readily determined.

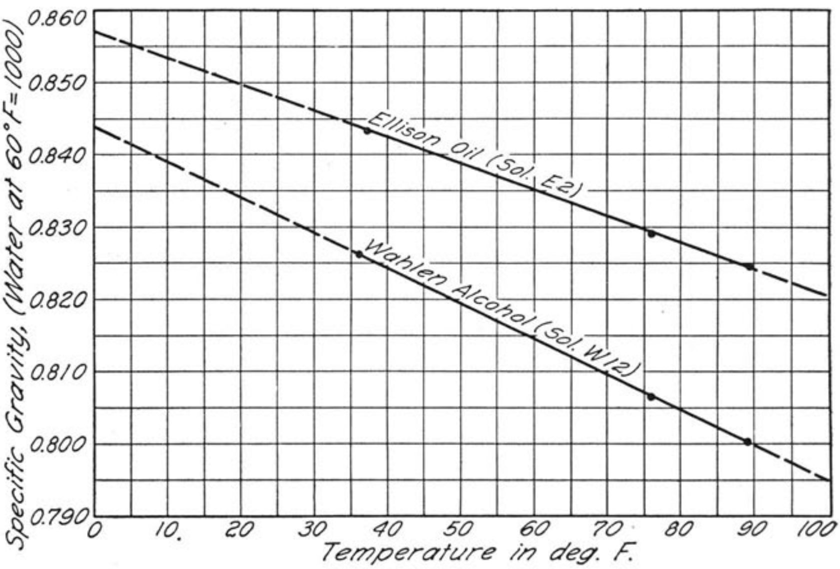

FIG. 2. SPECIFIC GRAVITY CURVES FOR WAHLEN GAGE ALCOHOL AND ELLISON GAGE OIL

A similar curve is shown in this figure for the Ellison gage fluid, since the height to which the liquid will rise in the tube, for a given pressure, is an inverse function of its specific gravity. The gage scales are calibrated for a certain temperature, that is, for a certain specific gravity of the liquid, and at other temperatures a correction must be applied according to the gage temperature at the time of the observation and the magnitude of the reading.

There are other possible sources of error in Ellison gage readings, however, such as curvature of the tube, inaccuracy in scale graduation, etc. To evaluate these the four Ellison gage tubes and the Wahlen gage were all connected to the same source of pressure, which could be controlled at will. Virtually simultaneous readings were taken on the five gages for a series of pressures of from 0.05 in. to 0.8 in. of water, the latter figure representing the maximum capacity of the Wahlen gage. Assuming the Wahlen gage readings, when converted into inches of water by multiplying by the specific gravity of the alcohol at the gage temperature, to be correct, the corresponding Ellison gage readings, corrected for temperature for each scale, were compared with them, and any discrepancies tabulated as calibration corrections to be applied to the respective Ellison gage readings. These corrections were small, three or four thousandths of an inch at the most. They were combined with the temperature corrections for various temperatures and the total corrections arranged in tabular form.

The pitot tubes used to obtain velocity pressures were of two types, those used for traversing and those used for center velocity pressures. Both types are shown in Fig. 1, the latter type being curved for use in the upright stands shown in Fig. 1. The static tubes are similar in size and appearance to the center-velocity pressure type of pitot tube, but have no central core for registering total pressure.

These tubes were connected to the gages by a ¼-in. inside diameter, 3-ply air hose which was cut into standard 50-ft. and 100-ft. lengths, and provided with fixed brass nipples on each end for connection to other tubes or the gages by means of short lengths of soft 5 x 2 mm. pure gum tubing. This equipment is illustrated in Fig. 1. Tubing lines were frequently tested for leaks and care was taken to prevent injury to them from sharp pieces of coal or otherwise. The pure gum connections were renewed at frequent intervals. No particular attempt was made to have the high-pressure line the same length as the low-pressure line, as tests failed to reveal any difference in gage behavior or readings between balanced and unbalanced lines.

Psychrometric data were taken with a portable sling psychrometer, both thermometers of which were graduated to 1 deg. F. and readings estimated to 0.5 deg. These determinations are well within the accuracy required for this work.

A mercurial barometer was used, the scale being graduated to 0.1 in. and readings estimated to 0.01 in.

III. Cross-sectioning and Mapping

5. *Offset Cross-sectioning.*—In the original field work the area of the cross-section was determined by taking horizontal measurements at the roof and floor and usually at one or two intermediate heights according to the irregularities of the ribs. Similarly, vertical measurements were taken from the corners of the roof and at such intermediate points as irregularities in the roof and floor indicated. The floor corners were located horizontally with respect to the roof corners by taking offsets to the right or left from the tape plumbed down from the roof corners.

The section outlines were plotted from these dimensions on coordinate paper, scale 1 in. = 1.3 ft., and the area determined with a planimeter.

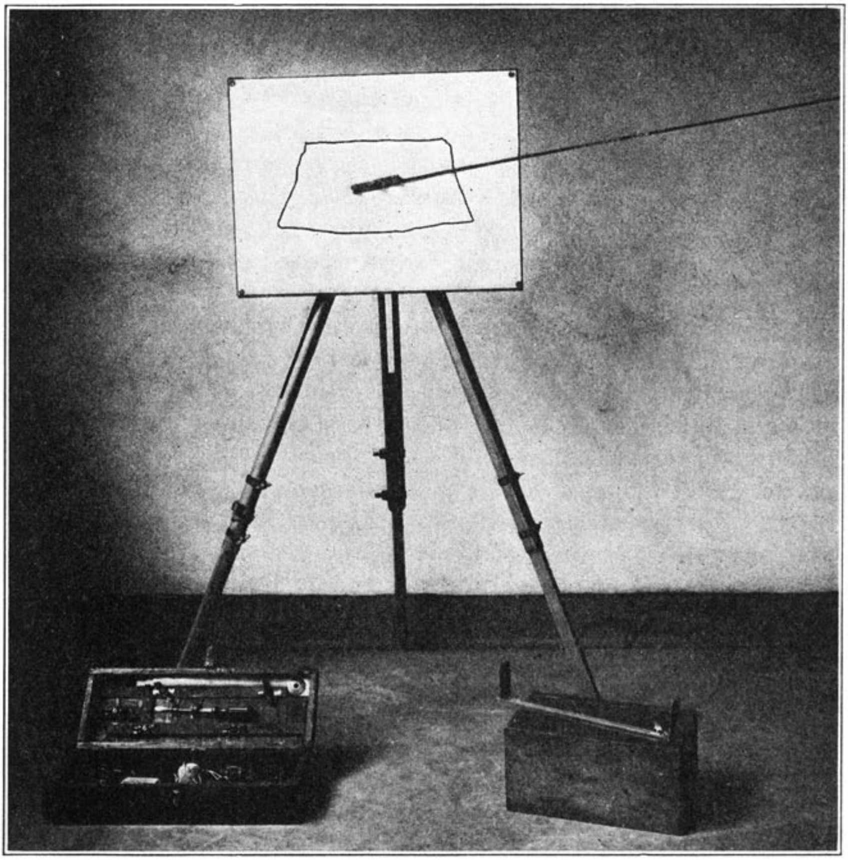

Fig. 3. Cross-sectioning and Mapping Equipment

6. *Instrumental Cross-sectioning.*—Later the cross-sectioning was done graphically in the field with the apparatus shown in Fig. 3. This consists of a plane table equipped with a specially-constructed head permitting the board to be mounted either horizontally, as used in mapping, or vertically for cross-sectioning. In cross-sectioning, a pivoted clamp is provided on the drawing surface which holds the zero end of a small steel tape at the center of the board and in such a way that the tape may be moved freely in the plane of the board.

The board was brought into the section by plumbing from the roof and sighting the corner points of the roof along the surface of the board. The tape was then extended to the point in the perimeter of the section which was to be plotted, and the distance from the center of the board to the point was called off to the nearest 0.1 ft., by one man. The other man immediately plotted this point on the paper along the graduated edge of the tape at a tape reading in hundredths of a foot equal to the distance to the actual point read in tenths of a foot, thus giving a scale of 1:10. In this way the tape gave direction and distance for plotting while being used to measure the actual distance.

This process was repeated at as many points as was thought necessary to determine properly the outline of the section, 15 or 20 points sufficing as a rule. This work went quite rapidly, four sections, previously marked off, being completed in an hour without difficulty. The perimeter of the cross-section graphs was determined afterward with a map measurer and the area with a planimeter.

The graphical method of cross-sectioning is obviously more accurate than the offset method, a comparison of results being shown in Table 1. This shows that occasional differences of 5 per cent or more in area and perimeter may be expected between measurements made by the offset method and those made by the graphical method. Oddly enough the maximum difference of 9.5 per cent in area at section E_2 was accompanied by a very small variation (0.6 per cent) in perimeter determination, and conversely the variation of 5.2 per cent in perimeter determination at C_4 is accompanied by a difference in area of only 0.1 per cent. This is not intended as the expression of a rule but rather as an exception, as in most of the cases there is more consistency between the two discrepancies.

However, it may be that the actual accuracy of the graphical method is not as great as might be expected, although unquestionably superior to that of offset measurements, for if the plotted perimeter be assumed to fall the equivalent of only 0.05 ft. outside of, or inside of, its actual position, the resulting error in area would be 1.75 sq. ft. for a section having a perimeter of 35 ft., which is an average value. This is equivalent

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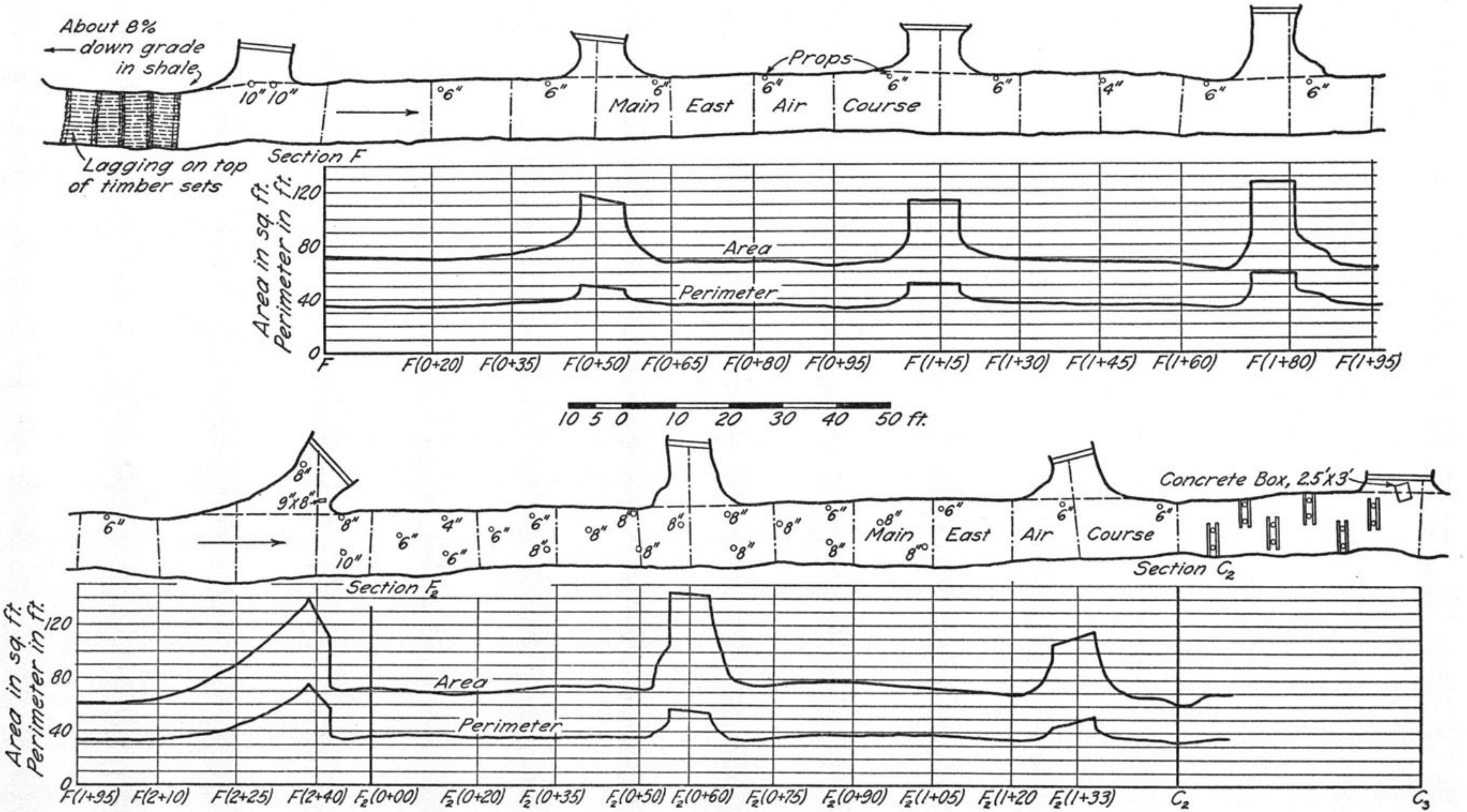

FIG. 4. DETAILS OF MAIN EAST AIR COURSE SHOWING CROSS-SECTIONAL AREA AND PERIMETER

to about 2.5 per cent of an average area of 65 sq. ft. It is at least safe to say that if cross-sectional areas are to be determined with an accuracy greater than this the work must be done with the greatest care, e.g., by greatly increasing the number of points in the graphical method, and by measuring the distances to them to the nearest hundredth of a foot. However, such fine measurements are meaningless unless the section has been specially prepared by smoothing the ribs, roof, and floor, both in the section proper and for some distance on both sides.

Cross-sections were taken at frequent intervals between sections F and F_2 along the Main East aircourse, with a view to evaluating the total rubbing surface and mean cross-sectional areas of the resistance test lengths involved for use in the standard resistance formula, $R = ksv^2$. In choosing a suitable interval between cross-sections it was decided to space them with respect to cross-cuts, having one fall fully within each cross-cut, and three between adjacent cross-cuts, or about 15 feet apart. The exact location of the individual cross-sections is shown in the plan of the entry, Fig. 4. They were designated by stations and plusses from one traverse or static section toward another.

It will be noticed that some sections are not exactly perpendicular to the course of the entry. In defining the section the roof was marked with a transverse chalk line through the proper "plus," the direction of the line being judged by the eye, no mechanical means being used to make it exactly perpendicular to the center-line of the entry. Some of the angles actually obtained were scaled from the plan and show a satisfactory result in most cases, with an extreme discrepancy of 10 deg. from true normality at section F. This was plainly visible after the line was established, but through oversight it was not corrected until some field work had been based on it. Even such a large variation produces a comparatively small error. This was the only case where there was a deviation of more than 5 deg. from the normal.

Areas and perimeters of these intermediate cross-sections are plotted in Fig. 4, every fourth one falling in a cross-cut. In making the calculations these cross-cut sections were given areas and perimeters determined by extending the line of the rib from which the cross-cuts are driven past each cross-cut. This is indicated in Fig. 4 by the broken line across the cross-cuts. The average area and perimeter including these nominal sections at the cross-cuts (68.0 sq. ft. and 35.3 ft. respectively) differ very little from the averages (68.9 sq. ft. and 35.5 ft. respectively) of those sections which fell within the entry proper.

TABLE 1

COMPARISON OF METHODS OF CROSS-SECTIONING

Instrumental Method			Offset Method					
Section	Area in sq. ft.	Perim-eter in ft.	(1) Area in sq. ft.	(2) Differ-ence	(3) % Diff. from Instr.	(4) Perim-eter in ft.	(5) Differ-ence	(6) % Diff. from Instr.
A.........			56.9			32.0		
C.........	64.8	32.5	61.1	−3.7	5.7	30.8	−1.7	5.2
D.........	63.6	34.0	62.9	−0.7	1.1	32.5	−1.5	4.4
E.........	60.3	32.0	58.8	−1.5	2.5	30.8	−1.2	3.8
F.........	72.3	36.5	72.9	+0.6	0.8	36.2	−0.3	0.8
G.........			61.6			32.4		
A_1........			81.6			39.6		
A_2........			68.4			37.2		
A_3........			65.5			35.6		
$C_6 = F_2$....	72.8	36.5	71.7	−1.1	1.5	36.0	−0.5	1.4
$C_2 = F_3$....	58.9	32.9	59.2	+0.3	0.5	32.4	−0.5	1.5
*C_3.......	82.8	40.0	86.0	+3.2	3.9	41.2	+1.2	3.0
C_4........	74.2	36.7	74.3	+0.1	0.1	34.8	−1.9	5.2
E_2........	62.9	34.2	68.9	+6.0	9.5	34.4	+0.2	0.6
E_3........	70.3	35.8	69.8	−0.5	0.7	34.4	−1.4	3.9
D_2........			73.8			36.4		
E_4........			59.2			31.2		
F_1........			54.9			33.2		
G_1........			62.8			33.2		
G_2........			72.9			36.4		
G_3........			55.2			31.2		

*C_3 — Cross-cut Section.
+ indicates Area or Perimeter, offset method, greater than Area or Perimeter, instrumental method.
− indicates Area or Perimeter, offset method, less than Area or Perimeter, instrumental method.

The dimensions to the nearest half foot of the rectangle most nearly approximating the cross-section in shape, perimeter, and area were listed for each section under the heading "nominal cross-section dimensions." The value of 6 x 11½ ft. was chosen as the most satisfactory mean, and was used in the formula for resistance for the test lengths covered by this survey.

7. *Mapping.*—Mapping was done with a plane table by the customary method of progression, except that the usual alidade was replaced by the peep sights illustrated in Fig. 3 and distances were measured with a 100-ft. steel tape. Direction was determined by sighting at a light held at the point to be mapped, and the distance plotted to scale along the graduated fiducial edge of the peep sights while still in position. The scale used in this work was 1 in. = 10 ft. which is large enough to permit the representation of any substantial sinuosities in ribs, or other irregularities or obstructions, such as timbers, etc.

Differences in elevation were determined at the overcast by sighting along the horizontal surface of the plane table at a level-rod held on the point in question. For short distances this gave sufficiently accurate results.

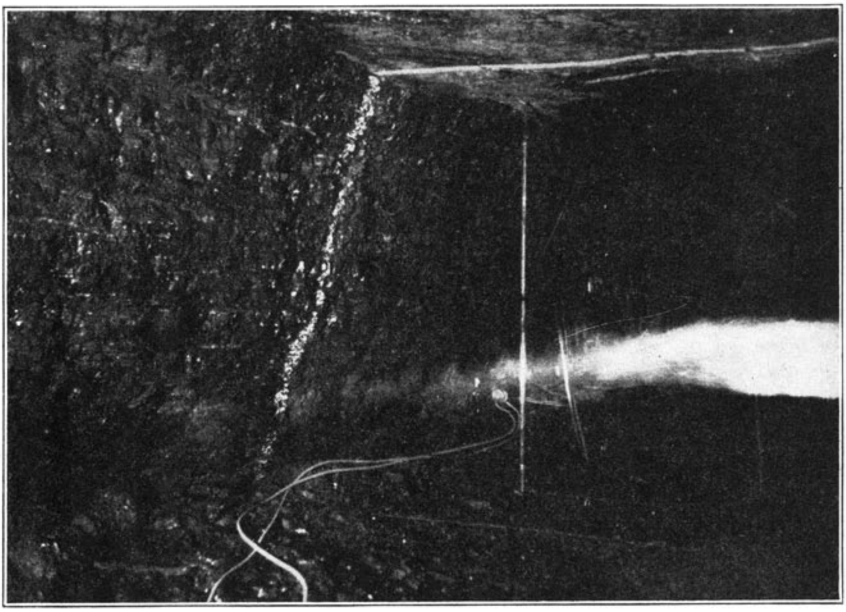

FIG. 5. TRAVERSE SECTION A

IV. MEASUREMENT OF AIR QUANTITIES

8. *Methods of Measurement.*—The main object in view at the beginning of this work was the development of a ready means of determining the quantity of air flowing in an airway, which could be used without any elaborate preparation of measuring stations, and which would give results with an accuracy suitable for engineering purposes. Simplicity and rapidity were thought desirable but not if gained at any material sacrifice in accuracy or by expensive preparation of a section. With this in view two methods of measurement, namely, by velocity-pressure readings and by anemometer, were tried repeatedly in the same locality for check, each on itself in successive measurements, and on each other. A discussion of the results obtained will form a later portion of this chapter.

9. *Air-Quantity Determination by Velocity-Pressure Measurement.*—The cross-sections selected for velocity-pressure traversing were chosen so that they were free from marked irregularities in outline and from obstructions, such as timbers, and had fairly uniform approaches and departures for as great a distance as feasible. The latter requirement meant that the section was chosen about midway between cross-cuts.

This was a convenient location as the gages could be placed in an adjacent cross-cut so that the observers were out of the direct air current while readings were being taken. No work was done toward re-shaping of the section itself or its approach and departure, beyond brushing loose coal from the roof and ribs and smoothing any debris on the floor. The section was marked across the roof, and in some cases down the ribs, with a chalk line (see Fig. 5), and measured as described in Chapter III.

The plan followed in traversing was to divide the traverse section into a number of subsections of approximately equal area, and to determine the air velocity at the center of each of these subsections. This velocity was attributed to the entire area of the subsection and, multiplied by that area, gave the quantity of air flowing through the subsection in unit time. A summation of these subquantities gave the total quantity for the section.

The maximum desirable area of subsections for routine work was arbitrarily taken as four square feet, and each section was subdivided on this basis, by dividing the central portion into equal squares measuring not more than two feet on a side. The remaining portions, adjacent to the ribs, which were not susceptible of this regular subdivision were divided into approximately equal areas of irregular shape according to the outlines of the section. Figure 6 illustrates the subdivision of section A into 12, 16, and 20 subsections.

For field purposes it was necessary to know the location of the center of each subsection with respect to a horizontal and a vertical datum. The roof was used as the horizontal datum and the distance of each subsection center point below it noted on the diagram, as well as the ordinates to the right or left from some plumb line chosen as a vertical datum. This was ordinarily taken from the middle point of the roof, but a roof corner was used occasionally, depending on the method of subdividing the area. This point of origin was marked on the roof and, so far as possible, the abscissae of all center points were also marked. Then in order to establish a center point, it was only necessary to plumb down the proper distance from the marked roof point. For those points which fell beyond the roof corners it was necessary to resort to some expedient such as plumbing up from a marked floor ordinate, or plumbing down from the adjacent roof corner and making a suitable offset at the level of the center point.

This procedure located only the tip of the pitot tube and in order to get it mounted and aligned properly it was necessary to mark on the roof and floor the positions for the top and bottom of the supporting column for each setting at a suitable distance (two feet in this work)

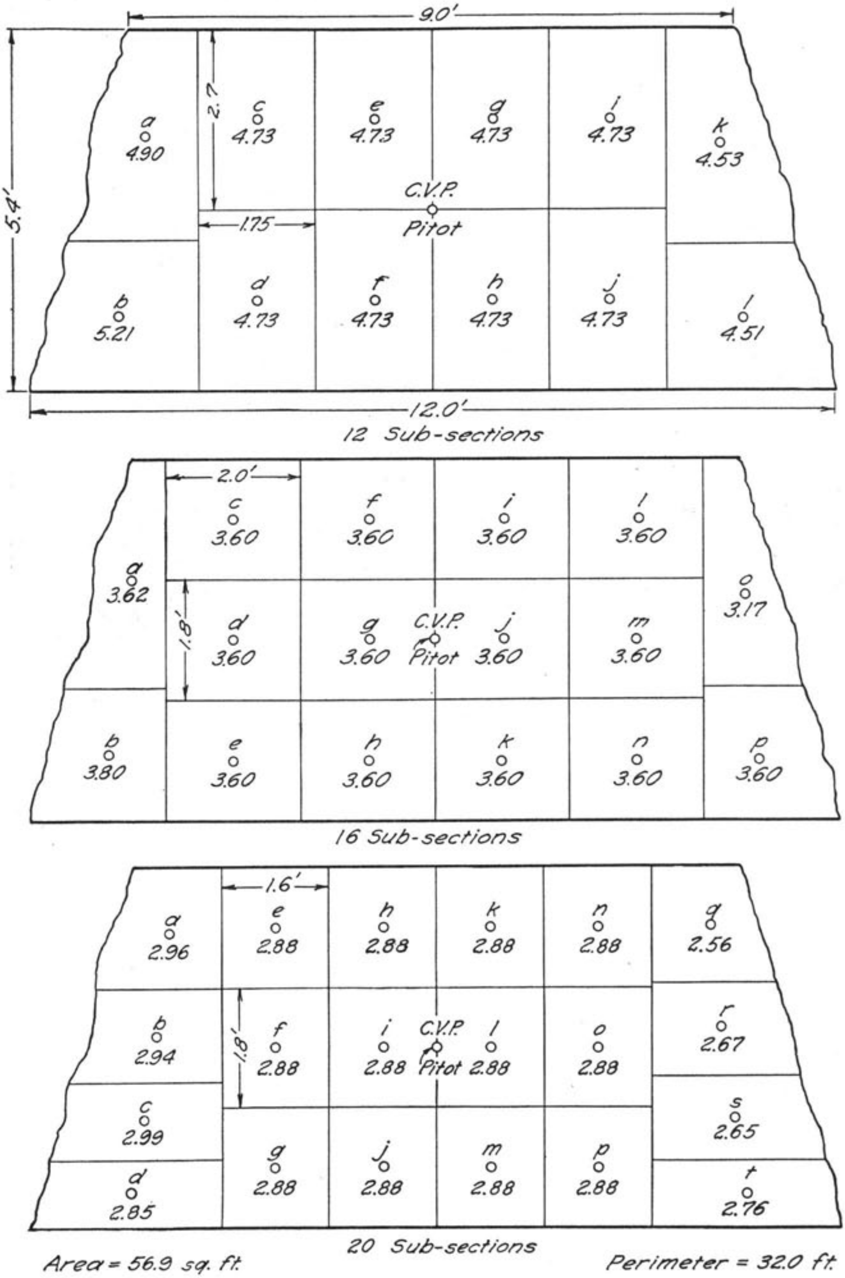

FIG. 6. SECTION A DIVIDED INTO 12, 16, AND 20 SUBSECTIONS

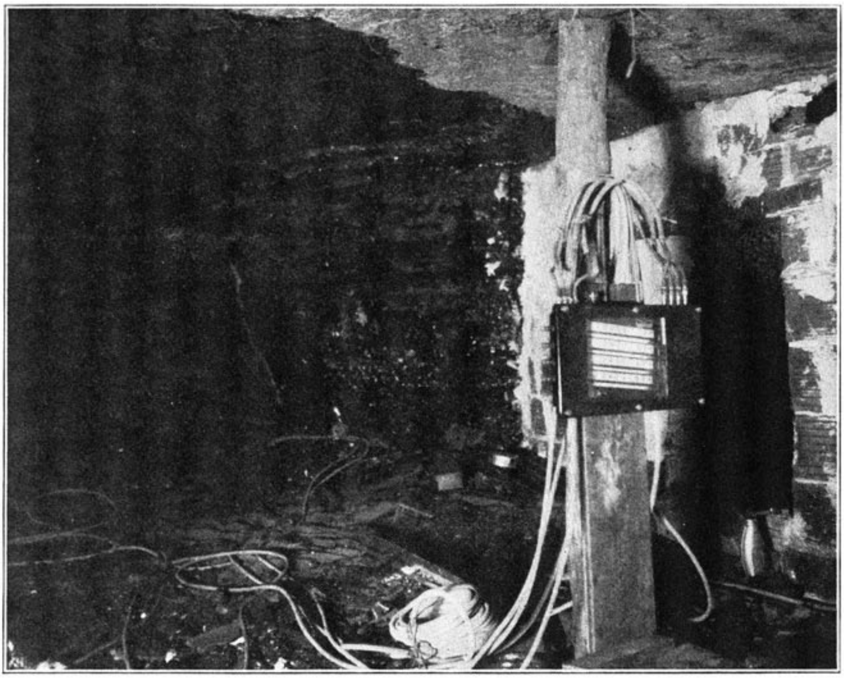

FIG. 7. ELLISON GAGE MOUNTED NEAR SECTION A

downstream from the traverse section. Proper horizontal pointing was obtained by looking up and down the entry for some distance and judging the mean course of the air past the section. This direction was marked on the roof from the origin to the offset section two feet behind. From this new origin the positions for the top of the column were measured and marked on the roof, allowance being made for the length of the offset arm by which the pitot tube was attached to the column. Corresponding positions for the bottom of the column were plumbed down to the floor and marked with knots on a string along the floor in the offset section. In this way the pitot tube was automatically brought parallel to the direction of air flow at each setup.

Having the rectangular subsections in vertical tiers it was necessary to set the column only once for a given tier and set the offset arm at the proper height for each center point. The tube was levelled by making it parallel to the bedding planes of the coal seam, which were, of course, virtually horizontal.

In order to study the relationship between the velocity at the center of a section and its mean velocity a second pitot tube was mounted

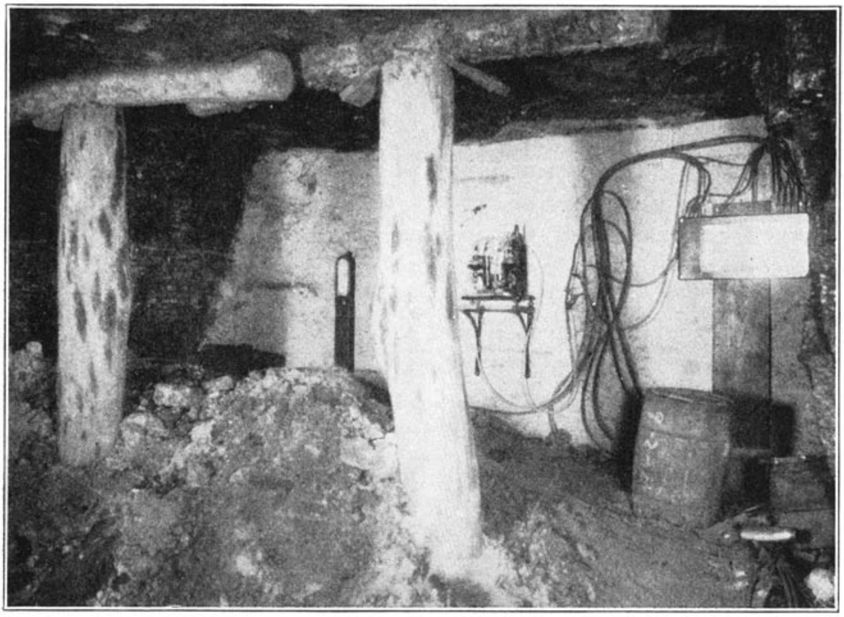

FIG. 8. ELLISON AND WAHLEN GAGES MOUNTED NEAR SECTION F

on a small stand and pointed upstream with its tip at the center of the traverse section, its position remaining fixed throughout the traverse.

In the earlier part of the work only the Ellison gage was used, the Wahlen gage being used later for traversing at lower velocities. As previously stated, the gages were put in a cross-cut adjacent to the traverse section. The Ellison was mounted on a flat board which was nailed to the stopping; the Wahlen gage was set on a small wooden shelf mounted on two brackets fastened to the stopping (see Figs. 7 and 8). In traversing, the total-pressure line from the pitot tube was connected to the high-pressure side of the gage, and the static-pressure line to the low-pressure side. The net pressure on the gage was the differenee between the two, or the velocity pressure of the air current at that particular time and place of pitot tube setting.

10. *Manner of Taking Readings.*—The plan generally followed in traversing was to take the barometric pressure and the wet- and dry-bulb temperature at a traverse section immediately preceding and following a traverse. As the time required for traversing was seldom more than three hours there was usually little change in these items. At section A each pitot traverse was preceded by an anemometer traverse occupying a very few minutes.

The use of the two pressure gages will be described separately as the procedure with the Ellison gage is quite different from that with the Wahlen.

11. *Traversing with Ellison Gage.*—In traversing with the Ellison gage index readings on each of the scales used were taken just at the beginning and at the end of the traverse. The initial and final readings on each scale usually agreed within one point (a point being 0.001 in. gage reading, the smallest unit of estimation). In traverses 2 and 4, section A, the final reading was two points less than the initial. In these cases the average value was applied to all pressure readings. In traverse 5A a disagreement of four points was observed between the initial and final readings probably due to the gradual shifting of the gage out of level, as indicated by a slight displacement in the level bubble. In applying the index correction to the gross pressure readings under these circumstances the change in index reading was distributed uniformly over the duration of the traverse. This assumption probably did not represent true conditions with great accuracy, and in order to maintain a more accurate value for later index readings a reading on an idle scale, when one was available, was taken at each setting of the pitot tube. This was known as the "dummy scale" and its readings remained constant as long as the gage stayed in a fixed position. A change in the "dummy scale" reading indicated an equal change in the index reading of the other scales, and was so applied in computing net pressures. Fortunately, however, index readings taken in the regular manner were very consistent in the subsequent work at section A, check readings not varying more than a point from each other.

The gage was read by focusing a hand flashlight on the meniscus and estimating its position with respect to the adjacent scale graduations to the nearest tenth of a space. This gave adequate and uniform illumination without the heating effect incident to the use of a carbide lamp near the gage. The middle scales, B and C, were better illuminated than the outside scales as there was no interference from the metal frame around the gage.

Pressure readings were observed and recorded according to the nature of the pressure to be determined. In general, the meniscus was watched for several seconds and the observer's impression of its average position recorded, rather than its position at a given instant. A series of such readings taken in succession would be used to determine the value of a given pressure. Traverse velocity pressures at A, where the velocity ranged around 600 ft. per min. (0.022 in. velocity pressure), were taken by averaging fifteen successive readings over fifteen-second intervals in the first traverse. Since the meniscus fluctuated over a range of five points or less this was later reduced to ten readings over ten-second intervals. This was continued through traverses 2 to 12. Usually three traverse pressure readings were taken, then a center-velocity pressure reading on an adjacent scale, then four traverse readings, a second center-velocity pressure reading, followed by three traverse readings and a final center-velocity pressure reading. This gave more center-velocity pressure determinations than were necessary to obtain a good average value for any one traverse, but it was thought that a relationship between fluctuations in traverse pressures and center-velocity pressure would be better brought out by frequent readings of the latter. In the remainder of the work at section A (traverses 13 to 19) five traverse pressure readings and one center-velocity pressure reading were taken at each setting of the pitot tube.

At other traverse sections (C to F) where the velocities ranged lower than 300 ft. per min. (0.005 in. velocity pressure) fluctuations were so slight that very few readings of one pressure were necessary, one or two sufficing in most cases.

A study of the relations of successive readings and the relative accuracy at different velocities may be of interest here. The scales are graduated in hundredths of an inch of water gage, each space covering about $\frac{1}{8}$ in., and readings estimated to the nearest 0.001 in. of water gage, or to the tenth of a scale space. It is generally conceded that the eye can subdivide such a space into fifths quite accurately and into tenths with fair accuracy. Experience in this work tends to confirm this as there is no certainty that readings taken by an observer at different times with the meniscus stationary and in the same position will be identical. Differences of one point were not unusual. Thus from this source alone there is a probable error of at least one point in each reading which, coupled with errors from other sources such as gage calibration, movement of the meniscus, etc., means a somewhat greater probable error in the readings. Granting the most favorable condition, with a probable error of only one point, it is seen that this is 20 per cent of the net reading for velocities as low as 300 ft. per min. and 5 per cent of the net pressure for velocities around 600 ft. per min. Since the velocity varies directly as the square root of the velocity pressure these errors in pressure determinations would give errors of about 10 per cent and $2\frac{1}{2}$ per cent respectively in the calculated velocities. Thus a fairly definite lower limit for velocities is indicated if accurate work is to be done with a gage of this type. This is strikingly illustrated in these tests where a series of traverses at section A, with a mean velocity of 530 ft. per min., gave no two total quantities for the section differing by more than 10 per cent from the average whereas two traverses at section E at a mean velocity of about 100 ft. per min. differed by nearly 100 per cent in quantity.

As previously stated, the net velocity pressures moved within a narrow range, usually less than five points, at any one setting. Occasionally the meniscus would move up or down out of its normal range, but such fluctuations were usually sharply marked and of short duration. The readings recorded at these times were not used in computing the average pressure. This excessive fluctuation was not as frequent an occurrence as one might expect, particularly on working days, with the continual movement of trips and opening and closing of doors.

The maximum, minimum, and mean net velocity pressures at each subsection were tabulated for six representative traverses at section A. From these data the amount by which the extreme (maximum or minimum) pressure differed from the mean was calculated as a percentage of the mean, this item being called the extreme per cent variation. Two of these tables, for traverses 1 and 17, and the average extreme per cent variation for each subsection in the six traverses analyzed (1, 2, 4, 13, 14, 17) are reproduced in Table 2. When the maximum

TABLE 2

NET VELOCITY-PRESSURE READINGS AT SECTION A*

Read on Ellison gage in thousandths of an inch of water.

Traverse 1, Smith, Date 6/27, Running, 15 readings per subsection, $V_m = 540$					Traverse 17, Smith, Date 7/7, Idle, 5 readings per subsection, $V_m = 500$				
(1) Subs.	(2) Max.	(3) Min.	(4) Mean	(5) Extr. % Var.	(2) Max.	(3) Min.	(4) Mean	(5) Extr. % Var.	†
a	26	22	24	± 8	21	20	20	+ 5	7
b	17	15	16	± 6	13	11	12	± 8	7
c	26	23	25	− 8	20	19	20	− 5	5
d	26	20	22	+18	22	22	22	0	6
e	21	18	19	+11	20	18	19	± 5	7
f	19	16	18	−11	16	15	15	+ 7	7
g	27	24	26	− 8	21	20	21	− 5	5
h	17	15	16	± 6	12	11	11	+ 9	8
i	23	18	20	+15	17	16	17	− 6	7
j	28	27	28	− 4	22	21	22	− 5	4
k	22	19	20	+10	19	17	18	± 6	8
l	19	16	17	+12	12	10	11	± 9	10
m	23	21	22	± 5	17	15	16	± 6	5
n	20	16	17	+18	16	14	15	± 7	8
o	11	9	10	±10	8	7	7	+14	10
p	7	6	7	−14	5	4	4	+25	18
Average				10				8	8

*See Appendix.
†Subsection averages for traverses 1, 2, 4, 13, 14, 17 at A.

pressure was farthest from the mean the extreme per cent variation was noted as plus, and conversely with the minimum pressure. Those which are marked plus and minus, the mean value being the average of the maximum and minimum, are a little more common than either the plus or minus quantities, which are about equal in number.

The average extreme per cent variation for the various subsections in these six traverses shows subsections l, o, and p to have the greatest variation with h, k, and n following closely. These are all "outside" subsections as will be noted in the middle diagram of Fig. 6, p. 19. The high value for p is of particular interest in view of the low absolute variation, one point, but the high relative variation. Furthermore, from Fig. 9 it will be seen that these subsections lie for the most part in zones of close isovel* stratification, more so than in the subsections symmetrical with them, and hence greater fluctuations in velocity might well be expected. Subsections g and j, adjacent to the center, have the lowest per cent variation.

As a rule the center-velocity pressure readings for a given traverse ranged within three points or less, although occasionally wider fluctuations were noted.

12. *Index Readings of Wahlen Gage.*—The use of the Wahlen gage differs from that of the Ellison gage principally in that the meniscus must be brought to a fixed index line (by a manual process) instead of its position being determined with respect to the index by use of a graduated scale. This, coupled with the higher sensitivity of the gage, requires greater care and skill than is demanded in the use of the Ellison gage. Furthermore, the gage is very responsive to slight changes in position which adds to the difficulty attending its use because the gage must be touched in setting the meniscus with the micrometer screw. These characteristics are reflected in the inconstancy of index readings found in this work.

Oddly enough the Wahlen gage apparently gave no trouble during the first few traverses in which it was used. This was at section G and for each of the first five traverses an initial and a final index reading only were taken. In two of these (1 and 3) the final index was identical with the initial, while in traverse 2 it differed by three points (a point on the Wahlen gage being one ten-thousandth of an inch of alcohol, the

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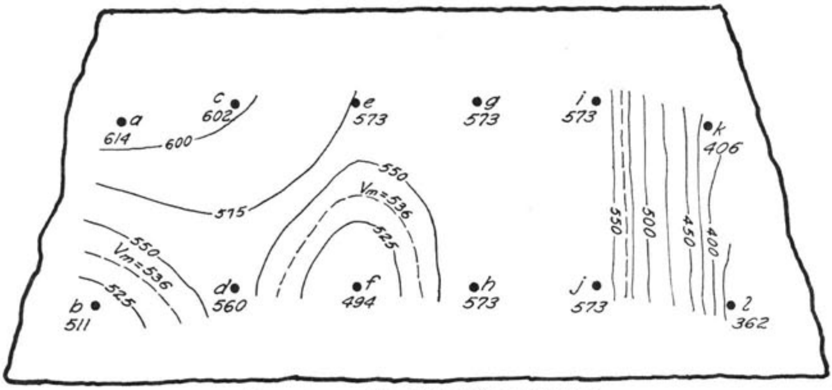
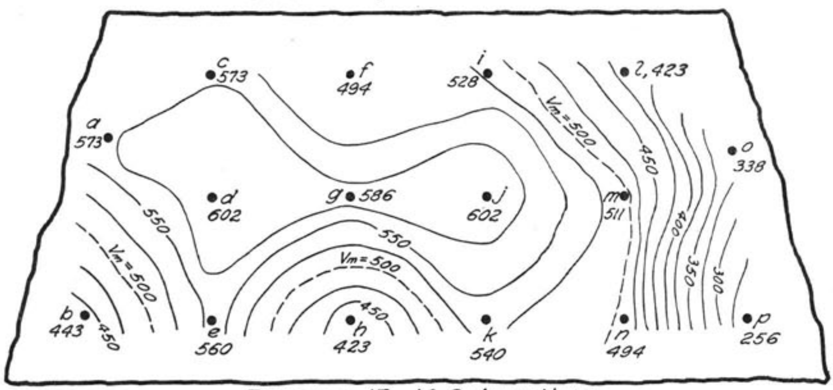
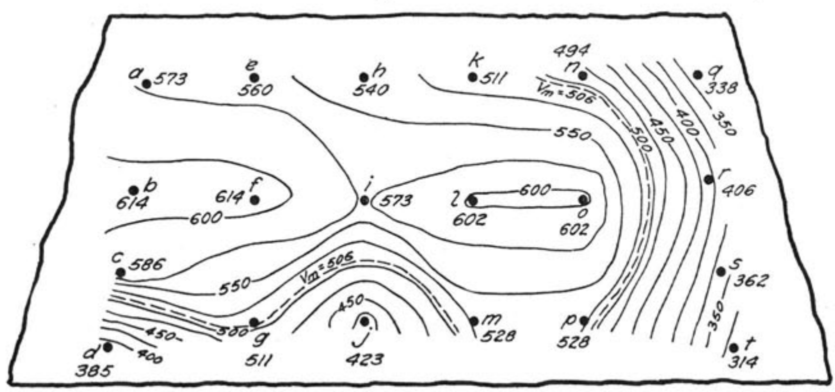
*An isovel is a line connecting points of equal velocity in a given cross-section.



Traverse 15, 12 Subsections



Traverse 17, 16 Subsections



Traverse 16, 20 Subsections

FIG. 9. ISOVEL DIAGRAMS FOR SECTION A, TRAVERSES 15, 16, AND 17

smallest unit of estimation). In traverse 4 the final index was reported as "O. K." and in traverse 5 no notation concerning it was made, the presumption being that it agreed closely with the initial index. In traverse 6, however, the final index was 14 points higher than the initial, and in traverse 7 a series of four index readings taken in immediate succession was noted just before and just after the traverse. The initial series was -1, -1, $+1$, and $+3$; the final series was -7, -4, -8, -11, indicating a substantial change in true index reading. This failure to get closely agreeing successive readings led to the adoption of a different plan for obtaining index corrections. In traverses 8, 9, and 10 index readings were taken at each traverse tube setting, the readings being repeated in each case until two or three were found to agree with each other within a point or two. Only these closely agreeing ones were used in calculating the index correction to be applied. This practice, modified to the extent of taking one series of index readings for two traverse settings, was continued through traverses 11 and 12 at G and traverses 3 and 4 at F.

Out of nearly 125 series of index readings taken in this way only 17 contained readings which were discarded as erratic, although the limits of acceptance were widened more than originally planned. Forty of the series met the specifications originally adopted, i.e., having three readings, no two of which differed by more than two points. Twenty-six of the accepted averages involved readings which differed by 3 points or more.

There is a question as to whether the average of such a series of readings is of more value than a single reading in the series, for at a given instant when a pressure is read, there must be a micrometer setting corresponding to zero pressure conditions which may be even farther from the average used than any single reading in the series. With this in mind, only one index setting was made for each two traverse tube settings in the remainder of the Wahlen-gage traverses. These index readings varied within one traverse much as the individual readings varied from each other in a series. The widest range of 12 points between maximum and minimum values was experienced in two traverses and in such a case the mean of all the index readings of the traverse was nearly the average of the two extremes. The average range of movement of the index for these traverses was nearly eight points; whereas the corresponding figure for the five traverses in which a series of index readings was taken was 13 points with a maximum range of 19 points in one traverse.

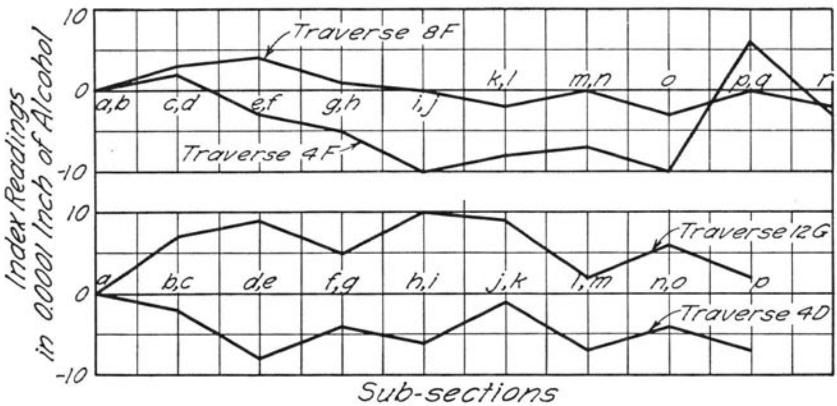


FIG. 10. VARIATION OF WAHLEN GAGE INDICES FOR FOUR TRAVERSES

Fig. 10 shows the plotted positions of the indices for the various sub-sections in traverses 8F, 4F, 12G, and 4D. There is a suggestion of a cyclic movement which is without apparent cause.

The explanation of this variability in index behavior probably lies in a number of contributing causes. Changes in level must play a relatively small part since the readings were taken within a minute or so of each other in a given series. While settling of the gage or movement of its support might account for differences in reading taken two or three hours apart it would hardly affect readings taken in rapid succession. Another possible source of error is in differential temperature changes between the two bulbs. While underground temperatures are so constant that the effect of eddying air currents is negligible, such changes might arise through proximity of the observer's hand or face, or from lights held near the gage, which is so sensitive to heating that the meniscus may be disturbed by bringing the hand near one of the bulbs. However, computation indicates that a difference of temperature of 1 deg. F. between bulbs would bring about a movement of the meniscus equivalent to less than one point of pressure due to expansion of the liquid. If a bulb were completely closed and the temperature of the air above the liquid changed 1 deg. F., a change in pressure of about 0.1 in. of alcohol would result. But the bulbs are not actually closed and the pressure differential would tend to be dissipated by movement of air in or out of one or both bulbs. Any lack of perfect adjustment in this way would result in a pressure differential in the gage, and if it amounted to only 1 per cent of the theoretical pressure change it would be equivalent to 10 points gage pressure. Furthermore, expansion and contraction of the glassware is probably a major item in the variability of the index. Thus it would seem that small, undetected temperature differentials between the bulbs might have been responsible for much of the inconstancy in index readings.

It was found that different readings were obtained if the meniscus were brought up to the index line from below, than if the reverse action were performed. This is probably due to lost motion in the micrometer and the tendency of the movable bulb to "hang" in its guides. The discrepancy was obviated by invariably bringing the meniscus up to the line, thus moving the bulb against the force of gravity. This kept the micrometer snug against its support and gave a constant condition of approach of the meniscus to the index.

Another point of difficulty was in judging when the meniscus was on the index line. This was to some extent a matter of illumination. The gage was lighted by a hand flashlight held close to the index tube and reading was assisted by having a white reflector behind the tube. With good light the meniscus was plainly visible and was usually sharply defined and well-shaped, although this depended to some extent on the rapidity with which it was brought up through the tube, a rapid, continuous movement giving a more rounded meniscus than a slower, halting movement. This, coupled with the inevitable variation in judgment of the contact between meniscus and index line, probably accounts for a part of the inconstancy of the index readings.

Another source of error is in the inertia and friction of the relatively large mass of liquid to be moved, which cause the meniscus to respond differently to quick movements than to slow ones. It is significant in this connection that the micrometer can ordinarily be moved through two or three points without moving the meniscus.

All in all, it may be said that the great sensitivity of the instrument makes it so responsive to slight variations in conditions of use that the benefits of its possible precision are partly nullified by its uncertain behavior. The extent to which this is true will be discussed more fully in taking up pressure measurements.

13. *Pressure Readings with Wahlen Gage.*—Taking pressure readings involves the errors and difficulties incident to index readings with the additional difficulties arising from a moving meniscus. Here, also, it was found that readings of a given pressure taken in immediate succession did not agree closely in spite of careful technic, and the variations were much more severe than those with index readings. This is to be expected from the irregularities present in underground air flow and pressures.

After a period of trial with shorter methods the plan was adopted of taking successive readings at each traverse-tube setting until a well-defined group falling within a narrow range could be noted. Occasionally this required only two or three settings, the meniscus being brought up to the index line each time. Sometimes a dozen or more readings had to be taken, the average number of readings in more than 100 series being six. In these series the extreme variation, using all the values obtained, ranged from nothing in one case to nearly 200 per cent, the average extreme variation for the eight individual traverses so involved ranging from 45 to 16 per cent with an average for the eight traverses of 30 per cent.

The foregoing extreme variations in results are materially reduced if the scattered and variant readings are eliminated as was planned during the field work. On this basis the average number of readings accepted in each series was 4.5, representing an average elimination of 1.5 readings per subsection (or series). The average extreme variation for the individual traverses is reduced to a maximum of about 20 per cent instead of 45 per cent and the average for the eight traverses from 30 to 12 per cent.

Were the quantities being measured constant so that discrepancies between successive readings could be attributed solely to errors in observation (including instrumental errors) fairly simple criteria could be established to control the elimination of faulty readings. However, as has been remarked, the pressures encountered in this work are known to be not constant, and it is probable that much of the discordancy is definitely attributable to fluctuations in air pressures. In fact, the varying of velocities at different points throughout a cross-section is no doubt continuous, and may be so diverse in its nature that no average value could be assigned to the velocity at one subsection which would have a definite ratio to an average for another subsection. Thus it would seem that the best approximation to average conditions would be reached by using a large number of readings, no matter how widely they differ, as long as there is no apparent reason for rejection (short-circuiting of air current, cars blocking entry, etc.) at the time of observation.

In some of the traverses with the Wahlen gage the method of setting the meniscus was changed from that described on p. 10 to what may be called the "average meniscus" method, where the meniscus was brought to the index line and observed under pressure for some time. The setting was adjusted until it was felt that the index line represented the average position of the meniscus. Under the low pressures experienced, 0.01 inch or less, the position of the meniscus usually ranged within ⅛ inch of the index line save for sudden fluctuations which would sometimes send it out of the constricted portion of the tube. A difficulty in this

TABLE 3

COMPUTATION SHEET FOR SECTION A, TRAVERSE 13

SECTION A
TRAVERSE 13
Observer: GmA
Recorder: a.j.H

DATE: July 6, 1925
MINE Working
Computer: a.j.H
Checker: CPB

Traverse Ellison Gage, Scale C, Index 0.003
C.V.P. Ellison Gage, Scale B, Index 0.009
Mercurial Barometer (B) 30.12 in.
Dry Bulb $(t) = 80°F$, Wet Bulb $(t') = 75°F$
Relative Humidity (p), from Tables, = 0.79
Vapor Pressure (f), from Tables, = 1.014

$$\text{Density of Air } (d) = \frac{1.3246(B - 0.378pf)}{459 + t} = 0.0732$$

$$\text{Velocity} = 1097\sqrt{\frac{h}{d}} = 4055\sqrt{h}$$

Average C.V.P 0.029
Index 0.009
Net C.V.P. 0.020
Center Velocity (V_c) = 575 ft. per min.
Specific Gravity of Wahlen Gage Solution ______

1	2	3	4	5	6	7	8
Sub-section	Velocity Pressure Reading Inches of Water	Index Correction	Net Velocity Pressure Inches of Alcohol	Net Velocity Pressure Inches of Water	Velocity Feet per Minute	Area of Sub-section Square Feet	Quantity Cubic Feet per Minute
a	0.024		—	0.021	588	3.62	2130
b	0.014		—	0.011	422	3.80	1600
c	0.025			0.022	602	3.60	2170
d	0.028			0.025	640	3.60	2300
e	0.022			0.019	560	3.60	2020
f	0.020			0.017	530	3.60	1910
g	0.024			0.021	588	3.60	2120
h	0.016			0.013	462	3.60	1660
i	0.020	−0.003		0.017	530	3.60	1910
j	0.026			0.023	614	3.60	2210
k	0.020			0.017	530	3.60	1910
l	0.015			0.012	442	3.60	1590
m	0.019			0.016	512	3.60	1840
n	0.016			0.013	462	3.60	1660
o	0.012			0.009	385	3.17	1220
p	0.009			0.006	313	3.15	990
q							
r							
s							
t							
					Totals	56.94	29240

$$\text{Average Velocity, } (V_m) = \frac{\text{Total of Column 8}}{\text{Total of Column 7}} = 514 \text{ ft. per min.}$$

method was that the meniscus tended to assume one position for an interval, then another at a higher or lower level, thus making it difficult to accept any one setting as an average position. Perhaps the best pressure determination possible would be an average of a large number of such observations.

Although the Wahlen gage micrometer gives graduated readings to one-thousandth of an inch of alcohol and estimated readings to the ten-thousandth of an inch, considering its extreme sensitivity as reflected in the variability of both index and pressure readings, it is doubtful if it is reliable closer than five ten-thousandths of an inch of alcohol, equivalent to four ten-thousandths (0.0004) of an inch of water. This is 10 per cent of 0.004 in. which corresponds to a velocity of 250 ft. per min. Since an error of 10 per cent in the velocity pressure would cause a 5 per cent error in calculated velocity it may be said that velocities lower than 250 ft. per min. cannot be measured with an accuracy as high as 5 per cent if we assume five points of gage reading to be the probable error in the velocity-pressure determination.

Repeated velocity-pressure traverses were made at three isolated sections on three different air currents. By an isolated section is meant one which was so situated that the same quantity of air was not measured elsewhere as a check. Of these three sections, section A had the highest velocity, which averaged 530 ft. per min., while sections F and G both averaged 230 ft. per min. All of the work at A, 18 complete traverses, was done with the Ellison gage. Of the 12 traverses completed at F, the first two were made with the Ellison gage only, the remaining 10 being made with the Wahlen gage. In four traverses both gages were used simultaneously. Twelve traverses were made at section G, all with the Wahlen gage.

14. *Reduction of Field Notes.*—The method of computation used in obtaining the quantity of air in cu. ft. per min. flowing past the cross-section from Ellison gage observations is illustrated in Table 3 which is the computation sheet for traverse 13A.

The average of the initial and final items of the psychrometric data are used in calculating the mean density of the air during the time of the traverse. The density is obtained by the formula* $d = \dfrac{1.3246\ (B - 0.378\ pf)}{459 + t}$ where B is the barometric pressure in inches of mercury, t the dry bulb temperature of the air in degrees Fahrenheit, p the relative humidity expressed as a ratio to unity, f

*For derivation of this formula see U. S. Bureau of Mines, Reports of Investigation No. 2527, p. 8.

the maximum pressure of water vapor at temperature t, and d the density of the air in pounds per cubic foot. Items B and t are taken from the field notes, and items p and f from psychrometric tables using the appropriate wet and dry bulb temperatures noted in the field. The psychrometric tables of the U. S. Department of Agriculture, Weather Bureau Bulletin No. 235, were used in this work. In the example given in Table 3 a difference of 5 degrees between wet and dry bulb temperatures at 80 deg. F. and 30 in. barometric pressure is equivalent to 79 per cent relative humidity ($p = 0.79$). Furthermore, the pressure of saturated aqueous vapor (f) at this temperature is 1.014 in. of mercury which, multiplied by the ratio 0.79 (p) and the constant 0.378, gives an adjustment of 0.303 in. of mercury to be subtracted from the barometer reading. This result multiplied by the constant 1.3246 and divided by 539 (459 + 80) gives a density of 0.0732 lb. per cu. ft.

It is necessary to know the density of the air to compute velocities from velocity pressures. This relationship is expressed by the formula* $V = 1097 \sqrt{\frac{h}{d}}$ where d is the air density as previously defined, h the velocity pressure in inches of water of the flowing air at the point in question as determined in the field, and V the velocity of the air in feet per minute.

It is evident that for a fixed density, such as is assumed to prevail throughout a given traverse, V varies directly as the square root of the velocity pressure, or is equal to a constant times the square root of h. That constant is $\frac{1097}{\sqrt{d}}$, or, in this case 4055; hence, for the density in question, 0.0732, we may write $V = 4055 \sqrt{h}$.

The entries on the computation sheet immediately following the calculated density relate to the index readings of the scales used in traversing (scale C) and in taking center-velocity pressure (scale B). Then follows the average of the readings on the latter scale, 0.029, from which is subtracted the index reading, 0.009, leaving a net center velocity pressure (h) of 0.020 inches of water. Solving for velocity, $V = 4055 \sqrt{0.020}$, gives a center velocity (V_c) of 575 ft. per min.

The data relating to the individual subsections are tabulated in vertical columns beneath the preliminary computations. Column 1 identifies the different subsections, sixteen in this traverse; their relative locations may be seen in Fig. 6. The appropriate velocity-pressure readings for each subsection, determined on the Ellison gage as previously

*Derived from fundamental formula $V = \sqrt{2gh}$, taking g as 32.16 ft. per sec. per sec. and the density of water as 62.366 lb. per cu. ft. at 60 deg. F.

TABLE 4

COMPUTATION SHEET FOR SECTION F, TRAVERSE 10

SECTION F
TRAVERSE 10
Observer: C.M.S.
Recorder: a.f.H.

DATE: August 4, 1925
MINE Idle
Computer: a.f.H.
Checker: C.M.S.

Traverse Wahlen Gage, Scale —, Index —
C.V.P. Ellison Gage, Scale B, Index 0.000
Mercurial Barometer (B) 30.11 in.
Dry Bulb (t) = 65°F, Wet Bulb (t′) = 63°F
Relative Humidity (p), from Tables, = 0.90
Vapor Pressure (f), from Tables, = 0.62

$$\text{Density of Air } (d), = \frac{1.3246\,(B - 0.378\,pf)}{459 + t} = 0.0754$$

$$\text{Velocity} = 1097\sqrt{\frac{h}{d}} = 3995\sqrt{h}$$

Average C.V.P. 0.009
Index 0.000
Net C.V.P. 0.009
Center Velocity (V_c) = 380 ft. per min.
Specific Gravity of Wahlen Gage Solution 0.812

1	2	3	4	5	6	7	8
Sub-section	Velocity Pressure Reading, Inches of Alcohol	Index Correction	Net Velocity Pressure Inches of Alcohol	Net Velocity Pressure Inches of Water	Velocity Feet per Minute	Area of Sub-section Square Feet	Quantity Cubic Feet per Minute
a	0.0040	−0.0001	0.0039	0.0032	226	4.13	930
b	0.0015	+0.0002	0.0017	0.0014	149	4.30	640
c	0.0002	+0.0002	0.0004	0.0003	69	4.37	300
d	0.0055	+0.0003	0.0058	0.0047	273	4.00	1090
e	0.0069	+0.0003	0.0072	0.0058	304	4.00	1220
f	0.0029	+0.0002	0.0031	0.0025	199	4.10	820
g	0.0051	+0.0002	0.0053	0.0043	262	4.00	1050
h	0.0084	−0.0002	0.0082	0.0067	325	4.00	1300
i	0.0041	−0.0002	0.0039	0.0032	226	3.91	880
j	0.0061	+0.0005	0.0066	0.0054	294	4.00	1180
k	0.0081	+0.0005	0.0086	0.0070	335	4.00	1340
l	0.0031	−0.0001	0.0030	0.0024	195	3.89	760
m	0.0059	−0.0001	0.0058	0.0047	273	4.00	1090
n	0.0059	−0.0001	0.0058	0.0047	273	4.00	1090
o	0.0021	−0.0001	0.0020	0.0016	159	3.90	620
p	0.0039	−0.0002	0.0037	0.0030	218	3.76	820
q	0.0036	−0.0002	0.0034	0.0028	212	4.08	860
r	0.0006	+0.0001	0.0007	0.0006	98	4.45	440
s							
t							
					Totals	72.89	16,430

$$\text{Average Velocity, } (V_m) = \frac{\text{Total of Column 8}}{\text{Total of Column 7}} = 225 \text{ ft. per min.}$$

described, p. 22, are entered in column 2. To each of these is applied the index correction of -0.003 (column 3) for scale C on which the traverse pressures were read. Column 4 is not used with the Ellison gage. The net velocity pressures are shown in column 5, and their corresponding velocities in column 6. Areas of the individual subsections as shown in column 7 are given in square feet, and are obtained from the field measurements. The quantity flowing through each subsection is obtained by multiplying the velocity at its center by its area, and is shown in column 8 in cu. ft. per min. The total of these subquantities gives the quantity for the entire section, 29 240 cu. ft. per min. in this case. Dividing this by the total area of the section, 56.94 sq. ft., gives a mean velocity (V_m) of 514 ft. per min. Summarizing: the items of columns 1, 2, 3, and 7 are from data previously obtained; column 5 = column 2 − column 3; column 6 = 4055 $\sqrt{\text{column 5}}$; column 8 = column 6 x column 7. The data of other Ellison gage traverses were reduced in essentially the same manner.

In case of Wahlen gage data some additional steps are necessary as indicated in Table 4 which shows the computation sheet of traverse 10F. The preliminary calculations for density and center velocity are similar to those just described. In this case the density was somewhat higher, 0.0754 as compared with 0.0732, giving a value of 3995 for the factor $\frac{1097}{\sqrt{d}}$.

Column 4 gives the net velocity pressure in inches of alcohol instead of inches of water. To correct for this it is only necessary to multiply the items of column 4 by the specific gravity of the Wahlen gage solution, 0.812, at the temperature of 65 deg. F. prevailing during this traverse. The results of this multiplication are shown in column 5, headed "Net Velocity Pressure—Inches of Water." These values are used in the formula $V = 3995\ \sqrt{h}$ to give subsectional velocities. The remainder of the process is the same as has been previously described.

15. *Discussion of Results at Section A.*—A glance at the quantity residuals, Table 5, shows that the individual quantities varied from about 6 per cent below to 10 per cent above the mean of the 18 quantity determinations, with an average variation of ± 3 per cent.

Applying a criterion developed as a guide in accepting or rejecting items in a series of repeated theodolite observations taken consecutively, namely, that an item whose residual is more than three times as great as the mean residual of the series should be rejected,* the data of traverse 6

*Briggs, Henry, "The Effects of Errors in Surveying," p. 36.

TABLE 5
PITOT TRAVERSES AT SECTION A, ELLISON GAGE*

(1) Tr.	(2) Date	(3) I.-R.	(4) Subs.	(6) Op.	(7) V_c	(8) V_m	(9) $\frac{V_m}{V_c}$	(10) % Var.	(11) Q	(12) % Var. from Mean	(13) Q_m
1	6/27	R	16	S	625	540	0.864	+1.2	30 740	+1.5	
2	6/29	I	16	S	675	552	0.818	−4.2	31 420	+3.8	
4	6/29	I	16	H	662	556	0.840	−1.6	31 670	+4.6	
5	6/30	R	16	H	620	557	0.899	+5.3	31 710	+4.8	
6	6/30	R	16	S	630	584	0.927	+8.5	33 270	+9.9	All = 30 280
7	7/1	I	16	S	620	521	0.842	−1.4	29 640	−2.1	R = 30 440
8	7/1	I	16	H	635	532	0.838	−1.9	30 290	0.0	I = 30 160
9	7/1	I	16	S	635	518	0.816	−4.5	29 480	−2.7	S = 30 130
10	7/1	I	16	H	637	550	0.863	+1.1	31 290	+3.3	H = 30 490
11	7/2	R	16	H	626	534	0.853	−0.1	30 440	+0.5	RS = 30 350
12	7/2	R	16	S	627	527	0.841	−1.5	30 010	−0.9	RH = 30 590
13	7/6	R	16	S	575	514	0.894	+4.7	29 240	−3.5	IS = 29 900
14	7/7	I	16	H	...	528	.....	.....	30 070	−0.7	IH = 30 420
15	7/7		12	S	...	536	.....	.....	30 490	+0.7	
16	7/7	I	20	H	614	506	0.825	−3.4	28 810	−4.9	
17	7/7	I	16	S	602	500	0.831	−2.7	28 450	−6.1	
18	7/8	R	12	H	...	521	.....	.....	29 630	−2.1	
19	7/8	R	20	S	...	501	.....	.....	28 510	−5.9	
Average					627	532	0.854	3.0	30 280	3.2	

Area Section A = 56.94
*See Appendix A.

would be the only unacceptable determination of the series. However, the two situations are not quite analogous since the measurement in question in surveying has a fixed value, which is probably not the case in this work since the quantity of air flowing is subject to variation, as will be discussed more fully later. Thus it would seem that wider limits of acceptance would be permissible in this work as there is an additional variation which may be more of an apparent error than a real one. Another justification for retaining the result of traverse 6A is that there was nothing of an erratic nature noted during the field work, the method of procedure and behavior of the gage apparently being consistent with that of other traverses with the exception of an unusually wide range in center-velocity pressure. If, then, this abnormally high result is to be attributed to an increase in quantity of air flowing, this fact should be reflected in an increased center velocity. This is, however, not the case, as the center velocity during this traverse was 630 ft. per min., virtually an average value. It is about 50 ft. per min. above and below the minimum and maximum center velocities of traverses 13 and 2 respectively which both differ less than 4 per cent from the mean. The fluctuations in center-velocity pressure were rather marked during traverse 6, ranging in net pressure from 18 to 29 points (Ellison gage). This traverse occupied two hours in the early afternoon of a working day, and notes concerning movement of trips and other disturbances were made twice during the traverse, although their exact effect on pressures could not be determined. Three center-velocity pressure readings (interspersed with traverse-velocity pressure readings) were taken at each subsection, giving 48 in all, the average of which was 25 points. While the only apparent explanation for the high quantity is an actual increase in air flow this is not borne out by an increased center velocity. There seems to be no consistent correlation between center velocity and quantity in this case.

That this is generally true is evident from an examination of the ratios of mean velocity to center velocity. They vary much as do the quantities, although not consistently higher or lower w'th higher or lower quantity. The average variation of the ratios $\frac{V_m}{V_c}$ from the mean, 0.854, is 3.0 per cent.

A study of all the data involved leads the authors to believe that the variations in columns 11 and 12, Table 5, represent in part a variation in the actual quantity of air flowing, and are not due entirely to instrumental and personal errors.

TABLE 6

PITOT TRAVERSES AT SECTION F*

(1) Tr.	(2) Date	(3) I.-R.	(5) Gage	(6) Op.	(7) V_c‡	(8) V_m	(9) $\frac{V_m}{V_c}$	(10) Var.	(11) Q	(12) % Var. from Mean	(13) Q_m	(14) Remarks
1	7/21	I	E	H	285	†142	....	....	†10 320	....	I = 17 100	V too low for Ellison
2	7/21	I	E	S	254	†180	....	....	†13 140	....	R = 16 270	V too low for Ellison
3	8/1	I	W	S	110	227	†2.06	....	16 570	−1.2	W = 16 760	All readings used
3	8/1	I	W	S	...	†221	....	....	†16 100	....	S = 16 350	Selective
4	8/1	I	W	H	336	247	0.736	+9.0	17 980	+7.3	H = 17 180	All
4	8/1	I	W	H	...	†246	.....	.....	†17 840	.....	IWS = 16 450	Selective
6	8/3	R	W	H	336	234	0.697	+3.3	17 050	+1.7	IWH = 17 740	Average meniscus
6	8/3	R	E	S	...	†203	†0.604	.....	†14 790	.....	RWS = 16 200	
7	8/3	R	W	H	310	214	0.691	+2.4	15 630	−6.8	RWH = 16 340	Average meniscus
7	8/3	R	E	S	...	†178a	†0.575a	...	†12 980a	.....		
					...	†230b	†0.742b	....	†16 730b	.....		

Area Section F = 72.89 sq. ft.
*See Appendix A.
†Not included in averages.
‡Determined by Ellison gage readings.
a—Taking A scale index as 0.018. Preferable value as it was read by H.
b—Taking A scale index as 0.017.

TABLE 6—(Concluded)

PITOT TRAVERSES AT SECTION F*

(1) Tr.	(2) Date	(3) I.-R.	(5) Gage	(6) Op.	(7) V_c‡	(8) V_m	(9) $\frac{V_m}{V_c}$	(10) Var.	(11) Q	(12) % Var. from Mean	(13) Q_m	(14) Remarks
8	8/3	R	W	S	310	227	0.732	+8.4	16 590	−1.0	Ell. av. = 13 470	Average meniscus
8	8/3	R	E	H	...	†204	†0.658	....	†14 850	.....	Sel. = 16 930	
9	8/3	R	W	S	310	217	0.700	+3.7	15 800	−5.8	All = 17 170	Average meniscus
9	8/3	R	E	H	...	†202	†0.652	....	†14 720	.....	Av. men. = 16 490	
10	8/4	I	W	S	...	†222	.....	....	†16 190	.....		Selective
10	8/4	I	W	S	380	225	0.592	−12.3	16 430	−2.0		All
11	8/4	I	W	S	380	225	0.592	−12.3	16 350	−2.5		Average meniscus
12	8/4	I	W	H	...	†241	.....	....	†17 570	.....		Selective
12	8/4	I	W	H	360	243	0.675	0.0	17 700	+5.6		All
13	8/4	I	W	H	360	242	0.673	−0.3	17 550	+4.7		Average meniscus
Average						230	0.675	5.7	16 760	3.9		

Area Section F = 72.89 sq. ft.
*See Appendix A.
†Not included in averages.
‡Determined by Ellison gage readings.

16. *Discussion of Results at Sections F and G.*—At section F both the Ellison and Wahlen gages were used; the Ellison alone on traverses 1 and 2, and the Ellison simultaneously with the Wahlen on traverses 6, 7, 8, 9. Here the mean velocity was 230 ft. per min. (velocity pressure = 0.0033) as compared with 530 ft. per min. at section A, and the futility of attempting to use the Ellison gage for low-pressure determinations is well illustrated in the results given in Table 6.

The average of six traverses with the Ellison gage was 13 470 cu. ft. per min. with an extreme variation of about 25 per cent, whereas the average of 10 traverses with the Wahlen gage was 16 730 cu. ft. per min. with an extreme variation of 7.5 per cent.

The effect of small differences in estimating fractional scale divisions on the Ellison gage (points of 0.001 in. water) is shown in the results of traverse 7 which were calculated with two different indices. One of these, 0.018, was read for traverse 6 by the observer of both traverses 6 and 7, and the other index, 0.017 ,was read by a different observer at the beginning of the succeeding traverse. The former value is unquestionally preferable but the two indices are used to illustrate the marked difference in resulting quantities, 12 980 and 16 730 cu. ft. per min. respectively. The value determined by simultaneous Wahlen gage readings was 15 630 cu. ft. per min. A comparison of the remaining Ellison gage quantities shows that they were consistently and substantially lower than corresponding Wahlen determinations. The wide differences in center velocity, ranging from 110 to 380 ft. per min. with intervals of 25 or more ft. per min. between adjacent values, is further evidence that the gage was being used beyond its lower limit.

The results of 10 traverses with the Wahlen gage are fairly consistent, considering that they were made on three different days and by different methods of taking readings, the mean residual for the 10 being ±3.8 per cent. In traverses 3, 4, 10, and 12 a number of instantaneous velocity-pressure readings were taken at each subsection according to the plan previously described, p. 29, and the results calculated on two different bases for each traverse; in one all values were used in obtaining the mean velocity pressure at a given subsection, in the other only the closely agreeing readings were used. In no case did the two quantities for a given traverse differ by as much as 2.5 per cent, the average of the quantities in which all readings were used being 17 170 and of those in which only selected readings were used 16 930 cu. ft. per min. Both these values are higher than the average of 16 730 for the ten traverses. However, in arriving at the latter figure only the quantities obtained by using all readings were used.

TABLE 7
PITOT TRAVERSES AT SECTION G, WAHLEN GAGE*

(1) Tr.	(2) Date	(3) I.-R.	(6) Op.	(7) V_c‡	(8) V_m	(9) $\frac{V_m}{V_c}$	(10) % Var.	(11) Q¶	(12) % Var. from Mean	(13) Q_m	(14) Remarks
1	7/24	I	S	282	200	0.710	−14.6	12 240	−12.8	All = 14 040	Single setting
2	7/24	I	H	113	221	†1.96	.....	13 540	−3.6	I = 14 040	Single setting
3	7/24	I	S	...	227	.....	.....	13 860	−1.3	R = 14 050	Single setting
4	7/24	I	H	...	231	.....	.....	14 170	+0.9	S = 13 700	Single setting
5	7/25	R	S	106	216	†2. +	.....	13 280	−5.5	H = 14 520	2 Readings
6	7/25	R	H	254	248	0.977	+17.6	15 250	+8.6	IS = 13 800	Index erratic
7	7/25	R	S	254	222	0.874	+5.2	13 630	−2.9	IH = 14 340	5 readings index questionable
8	7/28	I	S	310	240	0.774	−6.9	14 720	+4.8	RS = 13 450	Several readings, frequent index
8¶					†239	†0.772		†14 570			
9	7/28	I	S	283	231	0.816	−1.8	14 150	+0.7		Several readings, frequent index
9¶					†235	†0.831		†14 430			
10	7/30	I	H	283	242	0.856	+3.0	14 780	+5.3		Several readings, frequent index
10¶					†243	†0.858		†14 880			
11	7/30	I	S	284	229	0.807	−2.9	14 050	0.0		Several readings, frequent index
11¶					†232	†0.817		†14 220			
12	7/30	I	H		242	.....	.....	14 860	+5.8		Several readings, frequent index
12¶					†242	.....	.....	†14 860			
Average					229	0.831	7.4	14 040	4.4		

Area Section G = 61.35 sq. ft.
*See Appendix A.
†Not included in averages.
‡Determined by Ellison gage readings.
¶Selective readings.

In traverses 6, 7, 8, 9, 11, and 13 the meniscus was set for its average position at each subsection, one reading only being taken as previously mentioned (p. 30). The average value for the six quantities so obtained was 16 490 cu. ft. per min., a little below the average of the ten traverses.

An interesting point is brought out in the averages of quantities obtained by two different observers, five of the ten traverses having been made by each. The average for one (S) is 16 350 and for the other (H) is 17 180 cu. ft. per min. Comparing successive traverses on the same day the quantities of the first observer (S) are consistently below those of the second (H) both at sections F and G, with one exception. This consistent difference in pressure readings was noticed repeatedly while the work was in progress and could only be explained as the result of individual personal equation. No corresponding consistent discrepancy was detected in using the Ellison gage.

The Wahlen gage was used for the first time at section G, and exclusively for quantity determinations at that section. The Wahlen gage work just referred to at section F was done subsequently, and is, perhaps, from the point of view of experience, of more value. In fact, the results of the first seven traverses at section G (Table 7) must be regarded as of questionable value due to uncertain index readings. The last five traverses (8-12 inclusive) were computed on the two bases previously described (p. 30), the average with all readings being 14 510 and for the selective readings 14 590 cu. ft. per min. The maximum difference between two results for a given traverse was 2 per cent. Oddly enough, identical quantities were obtained by the two methods in traverse 12 although some corresponding subquantities differed. On the whole it seems safe to say that the two methods of interpretation will give results agreeing within two or three per cent for velocities around 250 ft. per min.

17. *Discussion of Results at a Split—Sections C, D, E.*—Sections C, D, and E are at a split as shown in Fig. 11. They were all traversed with the Ellison gage following the work at section A. Later, they were again traversed with the Wahlen gage, with the results shown in Table 8, which also includes the Ellison gage determinations. At section C these results compare favorably with those obtained with the Wahlen gage, the extreme variation of the three Ellison gage quantities being 4.7 per cent and the variation of either of the Wahlen gage quantities being 2.6 per cent from their mean. However, the number of traverses is too small to enable one to conclude that the Ellison gage could be used safely at such low velocities (mean value = 290 ft. per min., equivalent to 0.005 in. velocity pressure).

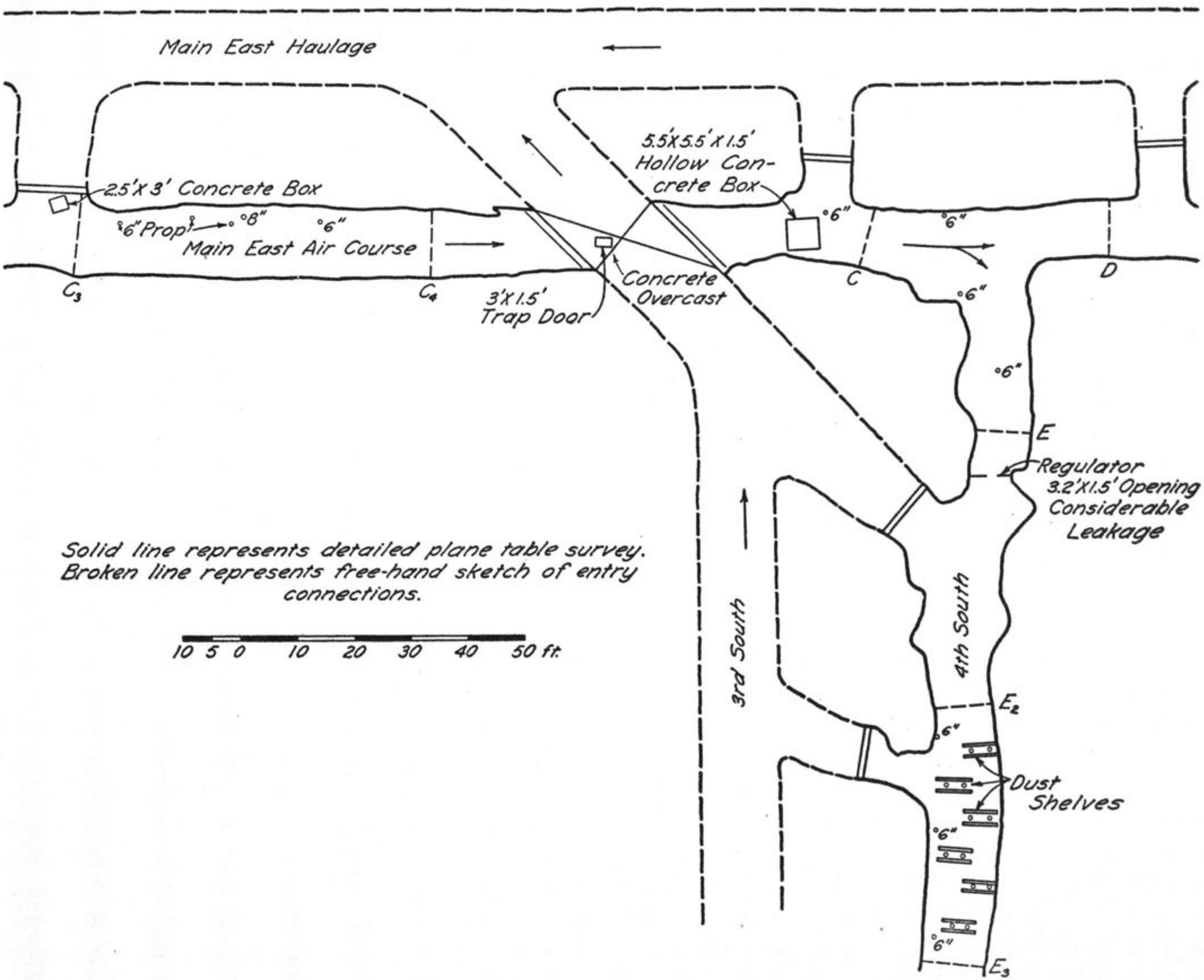


FIG. 11. DETAILS OF ENTRIES FOR SECTIONS C, D, AND E

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TABLE 8

PITOT TRAVERSES AT SECTIONS C, D, AND E*

(1) Tr.	(2) Date	(3) I.-R.	(5) Gage	(6) Op.	(7) V_c	(8) V_m	(9) $\frac{V_m}{V_c}$	(10) % Var.	(11) Q	(12) % Var. from Mean	(13) Q_m
						Section C					
1	7/13	I	E	S	323	279	0.864	+6.9	17 040	−3.0	I = 17 740
2	7/15	I	E	H	361	304	0.843	+4.3	18 550	+5.5	E = 17 720
3	7/18	I	E	S	379	288	0.760	−5.9	17 550	0.0	W = 17 360
4	8/5	R	W	S	358	277	0.774	−4.2	16 910	−3.8	S = 17 170
5	8/6	I	W	H	360	292	0.811	+0.4	17 810	+1.4	H = 18 180
Average					356	288	0.808	4.3	17 570	2.7	
Area Section C = 61.07 sq. ft.											
						Section D					
1	7/15	I	E	H	179	206	V too low for Ellison Gage		12 950		I = 9 650
2	7/18	I	E	S	179	116	V too low for Ellison Gage		7 280		E = 10 120
3	8/5	R	W	S	...	142			8 930		W = 8 820
4	8/6	I	W	H	...	138			8 720		H = 10 830
Average						151					S = 8 110

Area Section D = 62.92 sq. ft.
*See Appendix A.

TABLE 8—(Concluded)

PITOT TRAVERSES AT SECTIONS C, D, AND E*

(1) Tr.	(2) Date	(3) I.-R.	(5) Gage	(6) V_c	(7) Op.	(8) V_m	(9) $\frac{V_m}{V_c}$	(10) % Var.	(11) Q	(12) % Var. from Mean	(13) Q_m
Section E											
1	7/15	I	E	H	140	183	....		10 750		
2	7/18	I	E	S	127	100	....		5 870		
3	8/5	R	W	S	...	131a	....		7 690a		
						140b			8 230b		
4	8/6	I	W	H		168			9 840		
Average											

Area Section E = 58.77 sq. ft.
*See Appendix A.
a—Using negative quantities.
b—Considering negative velocity pressures as zero.

At sections D and E the Ellison gage determinations are notably out of line with the Wahlen gage results, and quite at variance within themselves. The Wahlen gage quantities checked closely at D but not so at E where difficulty was encountered in the way of negative velocity pressure readings at subsections c (net negative pressure 5 points) and m (net negative pressure 2 points). During the field work it was felt that this might represent an actual reversal of flow due to eddying in these subsections, which are both corner subsections as will be seen in Fig. 20.

However, the index readings for the entire traverse 3E were -10, -5, -11, -10, -9, -6, -9, -12 with the -5 being applied to a reading of -10 at subsection c and index -9 to a gross reading of -11 at m. The index at c is so out of line with the preceding and following indices that it may well be considered a faulty reading, thereby cancelling the negative velocity pressure. A slight error in either the index readings or pressure readings at subsection m would account for the apparent negative value there, so it is improbable that actual negative velocity pressures were registered.

If the result of traverse 3E be ignored and that of 4E (9840) accepted, and added to the mean of the two Wahlen gage determinations (8820) at D, a total quantity of 18 660 cu. ft. per min. in the two split arms is obtained, as compared with fully 1000 cu. ft. per min. less than this at section C, the source of the two split currents. This discrepancy must be attributed to errors in method for the most part, as changes in relative quantity during the course of the three successive traverses, occupying the major part of a day, could hardly account for this marked and consistent disagreement. Obviously the effects of errors become relatively more important as the pressures become lower, so it is probable that most of the difficulty is in the split arms where the velocities are very low, and that these results are unreliable. Notations, presumably left by a mine examiner, on Jan. 8, 1926, several months after this work was done, credit section D with 13 200 cu. ft. per min. at high fan speed and 12 000 cu. ft. per min. at low speed, and section E with 12 180 and 10 440 cu. ft. per min. respectively. No notation was found for section C, but both split-arm determinations are substantially higher than the quantities obtained by velocity-pressure traversing.*

18. *Anemometer Traverses.*—A series of three anemometer traverses of some sections was made immediately preceding or following each pitot-tube traverse. The anemometer was held at arm's length, and moved slowly in a path estimated to include the subsection centers so

*It is possible, but not probable, that there was a larger quantity of air in January than at the time when the velocity-pressure traverse was made.

Table 9
Anemometer Traverses at Section A*

(1) Pitot Tr.	(2) Op.	(3) Anem. Vel.	(4) Mean Anem. Vel.	(5) % Var.	(6) Mean % Var.	(7) Mean Pitot Vel.	(8) $\frac{V_p}{V_a}$	(9) % Var.
1	S	564 606 692	621	−9.2 −2.4 +11.5	7.7	540	0.869	+3.7
2	S	697 685 650	677	+3.0 +1.2 −4.0	2.7	552	0.816	−2.7
3	H	652 608 600	620	+5.2 −1.9 −3.2	3.4	...	.....	.....
5	H	675 662 653	663	+1.8 −0.2 −1.5	1.2	557	0.841	+0.4
6	S	632 625 623	627	+0.8 −0.3 −0.6	0.6	584	0.931	+11.1
7	S	662 621 621	635	+4.3 −2.2 −2.2	2.9	521	0.820	−2.1
8	H	571 600 655	609	−6.2 −1.5 +7.6	5.1	532	0.874	+4.3
9	S	590 579 609	593	−0.5 −2.4 +2.7	1.8	518	0.874	+4.3
10	H	653 668 619	647	+0.9 +3.2 −4.3	2.8	550	0.850	+1.4
11	H	642 676 661 691	668	−3.8 +1.2 −1.0 +3.5	2.4	534	0.799	−4.7
12	S	636 591 618	615	+3.4 −3.9 +0.5	2.6	527	0.857	+2.3
13	S	635 586 588	603	+5.3 −2.8 −2.5	3.5	514	0.852	+1.7
14	H	651 661 663	658	−1.2 +0.5 +0.7	0.8	528	0.803	−4.2
15	S	624 624 638	629	−0.8 −0.8 +1.4	1.0	536	0.852	+1.7
16	H	625 664 668	652	−4.1 +1.8 +2.5	2.8	506	0.776	−7.4
17	S	621 637 634	631	−1.6 +1.0 +0.4	1.0	500	0.793	−5.4
18	H	643 643 640	642	+0.1 +0.1 −0.2	0.1	521	0.812	−3.1
19	S	587 604 611	601	−2.2 +0.5 +1.7	1.5	501	0.834	−0.5
Average			633		2.4		0.838	3.6

Note—Average $\frac{V_p}{V_a}$ for observer H = 0.822; for S = 0.850.

*See Appendix A.

as to register a mean velocity for the entire section. The observer stood to one side of the instrument and practically in the section. Initial and final anemometer and time readings were noted and the average uncorrected velocity reading computed from them. After the first few traverses in which the whole area was covered at one time, necessitating the passage of the anemometer directly in front of or behind the observer, the traverse was made in two separate halves so that air flow past the instrument was unobstructed while it was registering. The net time required for traversing averaged a little more than one minute.

The results obtained by the latter method at section A are given in Table 9. It shows that successive readings varied from each other rather markedly, an extreme variation of more than 7 per cent from the mean of a series occurring in one case, with a maximum average variation of 5 per cent for a given series. However, this set of readings is exceptionally inconsistent, the mean residual of the other sets being less than 3 per cent with one exception. The mean velocities as determined with the anemometer are invariably higher than those determined by velocity-pressure measurements, but their fluctuations from series to series are no more severe as shown by a mean residual of 3.2 per cent for both sets of mean velocities. This indicates that the agreement of anemometer measurements was consistent with that of the Ellison gage determinations.

The ratio of mean velocity from velocity-pressure determinations (V_p) to mean anemometer velocity (V_a) was computed for each pitot traverse in an attempt to correlate the results of the two methods, or, in other words, to calibrate the anemometer against the Ellison gage velocities at the mean velocity of this section. The results are given in column 8, Table 9, and range from a minimum of 0.776 to a maximum of 0.931, this latter value being influenced by the unusually high quantity obtained in the pitot traverse. The average factor is 0.838.

No consistent personal equation between observers was noticed in using the anemometer, although successive measurements by different persons could be expected to differ more than those by either one.

Three sets of pitot and anemometer traverses at section C at velocities of less than 300 ft. per min. gave V_p/V_a ratios of 0.92, 1.18, and 0.95, indicating a marked inconsistency between the two methods. Since the Ellison gage was used for these low velocity-pressure measurements it is probable that some of the discordancy is due to gage inaccuracy. Individual anemometer velocities, however, varied by as much as 11.6 per cent from the average of a three-reading series in one case, with a mean variation for the three series of 4.4 per cent as compared with a similar value of 2.4 per cent at section A. At sections D and E where the velocity was little more than 100 ft. per min. successive readings within 5 per cent of each other were obtained, but the number of observations is too limited to be conclusive or even indicative.

In attempting to use the anemometer later it was found that it was running less freely than normal, so further velocity determinations by this method were abandoned. It is possible that it was beginning to tighten up at section C as indicated by the high $\frac{V_p}{V_a}$ ratio (average 1.02 as compared with 0.84 at A). This marked mechanical uncertainty would seem to be a factor militating against the use of the anemometer for accurate work of this kind. Obviously any calibration, no matter how accurately made, may be rendered very erroneous by a slight change in mechanical adjustment due to wear, dust and dirt accumulations, temperature changes, etc. Were the instrument thoroughly reliable in this respect it would seem that quantities could be determined as accurately with it under the conditions prevailing at section A, for example, as with the Ellison gage, provided the anemometer were calibrated under the actual conditions of use.

It must be admitted, however, that the anemometer, while in general use for routine mine ventilation work, is inherently unreliable for such work. Its delicate construction and the exposed position of the vanes, subjecting them to almost certain abuse, make for results of doubtful accuracy unless the instrument has been handled with extreme care.

Again, the common method of use, with the observer standing in the entry, is certain to cause readings that are considerably too high owing to the increased velocities produced by the reduction in area of the cross-section. This result is shown very well by comparing the mean average velocity at section A as determined by velocity-pressure traversing and by anemometer traversing, 532 ft. per min. for the pitot-tube method and 633 ft. per min. for the anemometer. The results for individual traverses can be compared by consulting Table 9.

Another example of this is shown in the discussion on page 45 where the quantities obtained by velocity-pressure traversing for splits D and E are very much less than the quantities determined by the mine examiner by the use of the anemometer.

A further source of inaccuracy, although giving the appearance of refinement, is the application of corrections obtained from calibration curves furnished by the makers of the instrument or by the Bureau of Standards. In the first place any calibration curve is of value only if the instrument is calibrated under the actual conditions of use. Secondly, the regular calibration curves are obtained by comparison methods or by whirling-arm methods at certain velocities, while in mine ventilation work the anemometer is used as an integrating instrument, being kept in constant travel back and forth across the section. It is obvious that a correction factor based on the average velocity is not an accurate factor particularly when variations in velocity are so irregular, as is shown in the isovel graphs, Figs. 9 and 21.

Experience has shown that the anemometer is reliable when used and cared for as a delicate, scientific instrument, and when calibrated under the exact conditions of use. The authors believe that it is possible to use the anemometer for accurate mine ventilation work if these requirements are complied with, but it would seem to be necessary to make a calibration so frequently in view of the differences in cross-sections, approach and departure characteristics, etc., that it is probable that reliance on pitot-tube traversing alone would be more satisfactory than introducing the anemometer as an additional instrument.

V. Measurement of Energy Losses

19. *Method of Measuring Energy Losses.*—Certain portions of the entries adjacent to traverse sections were used to determine the energy losses incident to the movement of air through airways. It was the aim in subdividing the entry longitudinally to divide it into units which were fairly uniform as to smoothness of rib, manner of timbering, if any, and freedom from major obstructions such as V-trough rock-dust barriers, overcasts, etc. The fineness of subdivision was limited by the necessity of taking lengths long enough to give a pressure loss sufficiently large to be registered on the gage. The shortest length of unobstructed entry used in this work was 150 feet.

The end sections of the resistance lengths were given the same letter as that of the adjacent traverse section through which the same air current flowed, and a subscript serial number in the order of their establishment; e.g., A_1, A_2, A_3, E_1, E_2, etc. Each such end section was marked by a line across the roof, drawn as nearly perpendicular to the course of the entry as could be judged by eye. They were then measured up to obtain the cross-sectional area. These sections were known as "static sections" because static pressure differentials between them were measured on the gages.

To accomplish this a static tube, Fig. 12, was placed in each end section of a length of entry and the two connecting tubes brought to the opposite sides of one of the gages. The resulting net pressure reading represented the difference in static pressures between the two ends of the test length, a static pressure drop being indicated if a positive

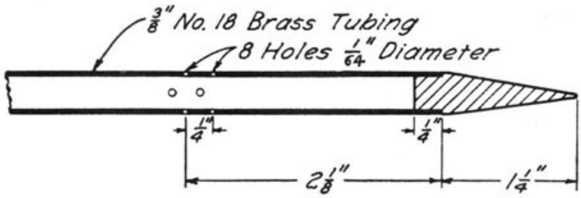

FIG. 12. STATIC PRESSURE TUBE

reading were obtained by connecting the static tube, which was farther upstream, to the high-pressure side of the gage. When these differential static pressure readings were taken in conjunction with traverses, as was commonly the case beginning with traverse 13A, it was customary to take one such reading for each set of velocity pressure readings. When they were taken independently of a traverse enough readings were taken to assure a proper average value. These readings usually fell within two or three points of each other in a given series, although there were a few exceptions to this.

If the results of different observations are to be strictly comparable they must be reduced to the values that would have been obtained under similar conditions if the air had been at a standard density, 0.075 lb. per cu. ft. The static pressure differentials were corrected to bring them to standard conditions by multiplying them by the ratio $\frac{0.075}{d}$, d being the density of the air at the time of observation. The velocity pressures were calculated for standard air density by using the formula $h = 0.000\,000\,0624\, V^2$, derived from the formula on p. 33, by substituting 0.075 for d and solving for h.

The reduction of a typical set of energy-loss data is worked out in detail in Table 10. The net result of the change in static and velocity pressures is the total pressure loss. The standard formula for ventilation resistance $R = ksv^2$ was transposed to the form $k = \frac{5.2\, ia}{lov^2}$ where i is the total pressure loss between end sections, a the cross-sectional area of the test length in sq. ft., l its length in ft., o the perimeter in ft., and v the mean velocity in ft. per min. Energy losses were calculated from the formula $h.p. = \frac{5.2\, iQ}{33\,000}$, Q being the quantity of air flowing and $h.p.$ the horse power represented by the total pressure loss i. For comparison these losses are reported on the basis of an entry length of 1000 ft. Nominal dimensions approximating average conditions as determined from the large scale map or field measurements were used throughout in this computation.

TABLE 10

ENERGY LOSS COMPUTATION FOR SECTION F, TRAVERSE 10

1	Date	August 4, 1925	
2	Running or Idle	Idle	
3	Section	F	
4	Traverse	10	
5	Quantity	16430	Cubic Feet per Minute
6	Portion of Entry	$F \cdot F_3$	(See Map)
7	Length	400	Feet
8	Area at F	72.89	Square Feet
9	Area at F_3	59.2	Square Feet
10	Velocity, (V_F)	225	Feet per Minute, $\left(\frac{\text{Item 5}}{\text{Item 8}}\right)$
11	Velocity, (V_{F_3})	278	Feet per Minute, $\left(\frac{\text{Item 5}}{\text{Item 9}}\right)$
12	Velocity Pressure, $V.P._F$	0.003	Inches of Water, from Tables
13	Velocity Pressure, $V.P._{F_3}$	0.005	Inches of Water, from Tables
14	$V.P._F - V.P._{F_3}$	−0.002	Inches of Water
15	Static Pressure Drop	0.015	Inches of Water, Field Notes
16	Density Ratio	$\frac{0.075}{0.074}$	$\frac{\text{Standard Density}}{\text{Actual Density}}$
17	Static Pressure Drop, Standard	0.015	Inches of Water, (Item 15 x Item 16)
18	Total Pressure Loss	0.013	Inches of Water, (Item 17 + Item 14)
19	Total Pressure Loss per 100 Feet	0.003	Inches of Water, $\left(\frac{\text{Item 18}}{\text{Item 7}} \times 100\right)$
20	Total Energy Loss	1090	Foot Pounds per Minute, (5.2 x Item 5 x Item 18)
21	Total Energy Loss per 100 Feet	273	Ft lb. per min., $\left(\frac{\text{Item 20}}{\text{Item 7}} \times 100\right)$
22	Nominal Area	69	Square Feet (See Map)
23	Nominal Perimeter	35	Feet
24	Nominal Velocity	238	Feet per Minute, $\left(\frac{\text{Item 5}}{\text{Item 22}}\right)$
25	k	68×10^{-10}	$\frac{5.2 \times \text{Item 18} \times \text{Item 22}}{\text{Item 7} \times \text{Item 23} \times (\text{Item 24})^2}$

Computer G.M.S. Checker N.A.T.

20. *Results Obtained at Section A.*—Three static sections were established adjacent to traverse section A, sections A_1 and A_2 being 310 ft. and 10 ft. above (upstream from) A respectively, and section A_3 being midway between sections A_1 and A_2. This is a straight entry, although the entire length has slightly sinuous, rough ribs. The top is coal for the most part, supported by occasional small props along the center line of the entry in the downstream portion of the length A_3-A_2. There is much debris on the floor in the way of loose coal, old cross ties, etc., some of it making obstructions two feet or more above the general floor level. The stoppings are of hollow tile or plastered sheathing and crosscuts are filled with gob for the most part.

The amount of timbering at the lower end is so small as to be negligible in its effect on the resistance of the entire length of 300 ft. between A_1 and A_2, and this portion may be described as a straight, comparatively untimbered entry with irregular ribs and floor, and with much debris, nominally 6 ft. high by 11½ ft. wide. Losses were determined in this length for five successive traverses at A (13 – 17), and in the 150 ft. length $A_3 - A_2$ in traverses 18 and 19, with the following results:

Resistance Section	Traverse	Nominal Velocity ft. per min.	T. P. L. in. of water	Energy Loss* (Horse power per 1000 ft. of entry)	k
	13	413	0.048	0.74	93×10^{-10}
	14	424	0.052	0.82	95×10^{-10}
$A_1 - A_2$	15	431	0.051	0.82	90×10^{-10}
	16	407	0.049	0.74	97×10^{-10}
	17	402	0.051	0.72	98×10^{-10}
				Average	95×10^{-10}
$A_3 - A_2$	18	444	0.026	0.81	84×10^{-10}
	19	427	0.025	0.73	88×10^{-10}
				Average	86×10^{-10}

Since the energy loss is nearly a direct function of the cube of the velocity, a higher energy loss should accompany a higher velocity, and a lower energy loss a lower velocity. This is roughly the case here.

The presence of some timbering in the stretch $A_3 - A_2$ would be expected to result in a higher value of k, but this is not the case. The entry was fairly well cleaned up near A_3, and it is possible that the lower actual velocity and less relative roughness combined to produce a smaller value of k in spite of the timbers.

*Energy losses are given so that a quantitative idea can be had of the power requirements. It must be remembered that the horse power required per 1000 ft. of entry represents only that particular kind and size of entry and with the air flowing at that velocity. If the velocity changes the power will change, the variation being about as the cube of the velocity.

21. Results Obtained at Section G.—A somewhat similar length of entry was studied in connection with the work at G which is in the return airway of a working panel. A static section G_1 was established 500 ft. upstream from traverse section G and section G_2 100 ft. downstream from it, giving a test length of 600 ft. It is straight, entirely in coal, with smooth roof and ribs. There are occasional falls of coal on the floor and a few sets of timbering. A series of 8-inch props along one rib supports power cables. Briefly, it may be described as a length of smooth, straight, slightly timbered, 5 x 12½ ft. entry, all in coal.

Static section G_3 was placed on the intake airway opposite section G_2, thereby including the resistance of the whole panel between the two. Reliable data concerning the energy losses in these test portions were obtained in four successive traverses, all on idle days. The results are as follows:

Resistance Section	Traverse	Nominal Velocity ft. per min.	T.P.L. in. of water	Energy Loss† (Horse power per 1000 ft. of entry)	k
$G_1 - G_2$	9	228	0.021	0.08	66×10^{-10}
	10	238	0.020	0.08	58×10^{-10}
				Average	62×10^{-10}
$G_3 - G_2$	8	238	0.106	0.25*	......
	11	227	0.105	0.23*	......

Results Obtained at Section F.—A third length of straight untimbered entry somewhat similar to those at A and G is that between F and F_2, the latter section being 249.5 ft. downstream from the former. There is a row of props about 20 ft. apart along one rib, and track has been left in place. The length is straight, all in coal, with smooth roof and ribs. Four closed crosscuts are included, one of them a "45" (see Fig. 4). The nominal size is 6 x 11½ ft. The results obtained in this resistance section are:

Resistance Section	Traverse	Nominal Velocity ft. per min.	T.P.L. in. of water	Energy Loss† (Horse power per 1000 ft. of entry)	k
$F - F_2$	4	261	0.008	0.09	46×10^{-10}
	6	247	0.007	0.08	48×10^{-10}
	7	226	0.007	0.07	56×10^{-10}
	8	240	0.007	0.07	50×10^{-10}
	9	229	0.007	0.07	55×10^{-10}
				Average	51×10^{-10}

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*Horse power for entire panel.
†See footnote, p. 52.

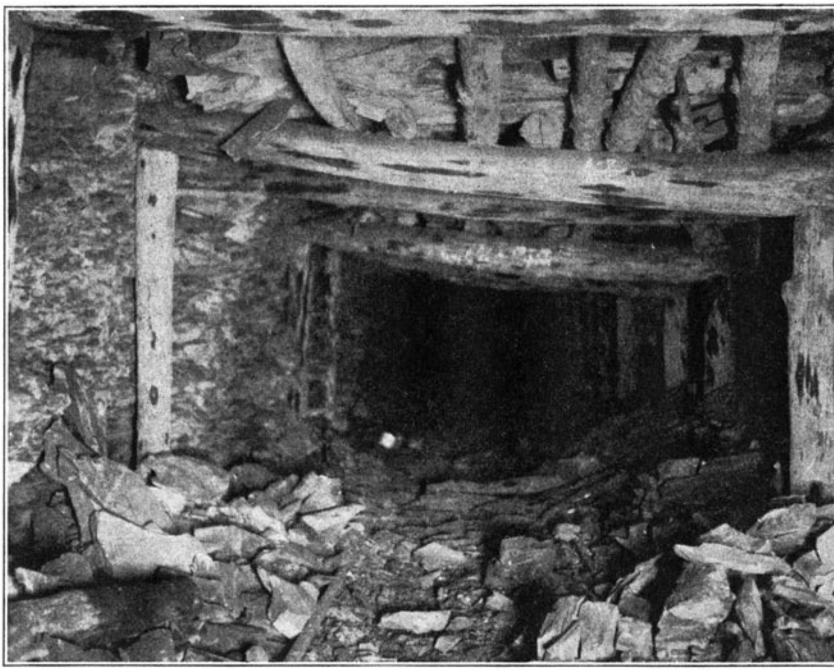


FIG. 13. TYPICAL PORTION OF ENTRY IN FAULT ZONE BETWEEN SECTIONS F_1 AND F

A short length, 150.5 ft., of timbered entry lies between (static) sections F_2 and C_2, its outlines and the location of individual props being shown in Fig. 4. It is a continuation of the $F - F_2$ portion and differs from it in the presence of timbers and absence of track. Direct measurement of its resistance was made with the Wahlen gage in connection with traverse 4F, the average total pressure loss being 0.0042 in. of water, with an energy loss of 0.08 h.p. per 1000 ft. of entry and a coefficient k of 42×10^{-10}.

Several observations were made of the drop in static pressure between F and C_2; this section is made up of $F - F_2$ and $F_2 - C_2$. The results follow:

Resistance Section	Traverse	Nominal Velocity ft. per min.	T.P.L. in. of water	Energy Loss* (Horse power per 1000 ft. of entry)	k
$F - C_2$	4	261	0.012	0.08	44×10^{-10}
	6	247	0.013	0.09	55×10^{-10}
	7	226	0.011	0.07	55×10^{-10}
	8	240	0.013	0.08	58×10^{-10}
	9	229	0.013	0.08	63×10^{-10}
				Average	55×10^{-10}

*See footnote, p. 52.

The rather low values of k resulting from the velocity of 261 ft. per min. obtained in traverse 4 do not seem to be acceptable when the total pressure losses are considered. There is a possibility that an error in traverse 4 resulted in a higher velocity being obtained than actually existed. This is the only way in which the authors can account for these low values of k, particularly for the timbered section $F_2 - C_2$.

A rather unusual type of entry lies between sections F_1 and F, (see Fig. 13) the former being 491.5 ft. upstream from the latter, and about 25 ft. below it in elevation. This latter condition is occasioned by a series of faults which left the portion of the seam in which F_1 is located substantially below its general level where F is located. The faulting is in steps, and the entry between F_1 and F passes alternately through coal and shale. Proceeding downstream from F_1 the entry is level and untimbered in coal for 91.5 ft. The succeeding 167 ft. rise through shale in a fault zone to the coal again; whence the entry runs horizontally in coal for 33 ft., and then rises through shale once more for 67 ft. The succeeding 106 ft. cross very marked faults and are partly in coal and partly in shale. The remainder is in the seam at the general coal horizon. The entry has been heavily timbered with 3-piece sets, roughly 5 ft. apart where the roof is in shale. In many cases the timbers have broken or become misplaced allowing large and very irregular accumulations of debris to form on the floor, with the consequent doming of the roof. The over-all cross-sectional dimensions vary from place to place, but on the whole approximate those of the same entry as regularly driven in the coal beyond section F, 6 x 11½ ft. A total pressure loss of 0.050 in. water at a mean velocity of 240 ft. per min. was noted between F_1 and F in connection with traverse 3F. This is equivalent to a power loss of 0.26 h.p. per 1000 ft. of entry and a coefficient k of 180×10^{-10}. These relatively high values are expressions of the roughness and irregularity of this passageway.

22. *Results Obtained at Section D.*—Another length of straight unobstructed entry studied was between sections D and D_2, the latter being 636 ft. downstream from the former. The entry is nominally 6½ x 10½ ft. in cross-section, entirely in coal, with smooth roof and floor and rather sinuous ribs, much like those at A. There is very little timbering. In traverse 4D with a mean velocity of 126 ft. per min. a static pressure drop equivalent to 0.0045 in. of water was registered by the Wahlen gage. This represents an energy loss of 0.01 h.p. per 1000 ft. of entry, and a coefficient k of 46×10^{-10}.

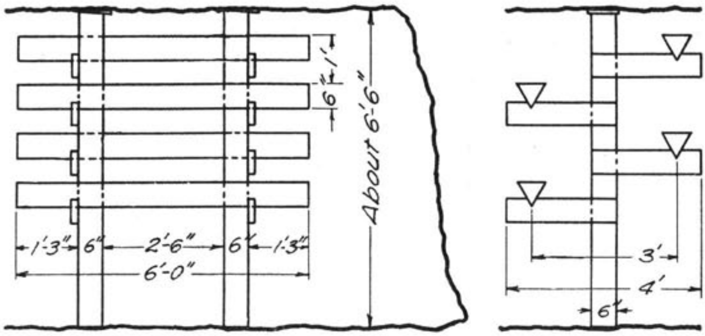


FIG. 14. ROCK-DUST BARRIERS

23. *Losses Due to Rock-Dust Troughs.*—A length of entry containing six sets of rock-dust barriers of the type shown in Figs. 14 and 15 was studied. The nominal size of the entry was 6 x 11½ ft. The results are as follows:

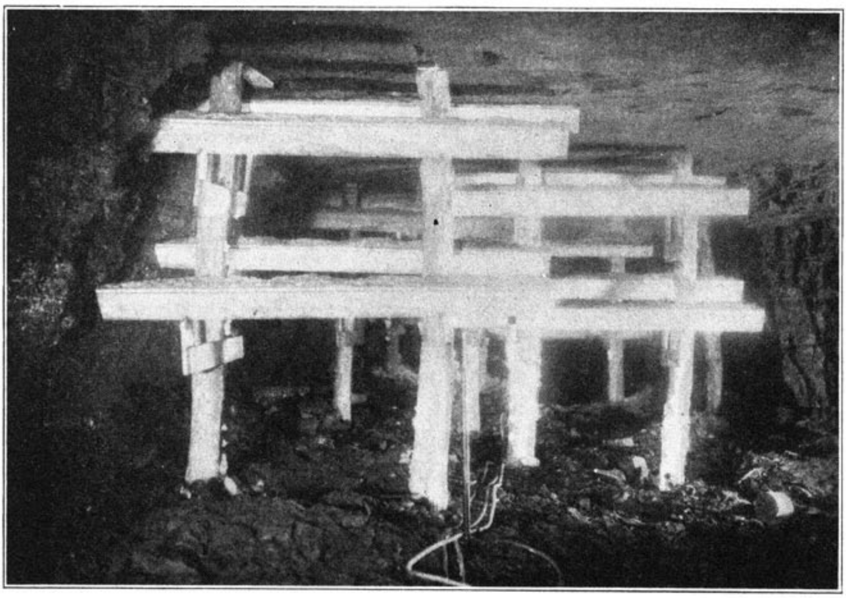


FIG. 15. ROCK-DUST BARRIERS WITH STATIC PRESSURE TUBE IN PLACE

Resistance Section	Length	Nominal Velocity ft. per min.	Traverse	T.P.L. in. of water	Energy Loss (Horse power per 1000 ft. of entry)	k
$C_2 - C_3$	45.5	258	5C	0.0123	0.76	420×10^{-10}

The energy loss represents the loss per 1000 ft. of entry with shelves arranged as shown in Figs. 4 and 11. This is about 0.035 h.p. for a section of six sets of troughs. The high value of k* indicates the effect of these barriers.

24. *Losses Due to an Overcast.*—The loss across one concrete overcast and its approach was determined. This overcast lies in the Main East air course about midway between sections C_4 and C which are 77 feet apart, C_4 being upstream from C. The overcast is shown in elevation in Fig. 16. The approach to and departure from it are

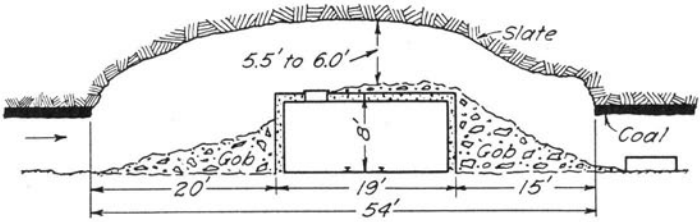


FIG. 16. ELEVATION OF OVERCAST BETWEEN SECTIONS C_4 AND C

very irregular in elevation and cross-section, each having a very uneven roof and the floor piled high with gob, as indicated in the elevation. (See also Fig. 17.) In connection with traverse 5C a total pressure loss of 0.016 in. of water was observed. This is equivalent to an energy loss of 0.045 h.p. for the length between C_4 and C, and a factor k* of 320 x 10^{-10}, using 6 x 11½ ft. as the nominal dimensions of the cross-section.

25. *Losses Due to a Regulator.*—The regulator just below E was a loosely-built patchwork of boards, having a major opening 1.5 x 3.2 ft., with many cracks and other openings for the passage of the air in and around the body of the regulator proper. A total pressure loss of 0.020 in. was noted between sections E and E_2 which are 49 ft. apart and include

*The values of k for the section with the rock-dust barriers and for the section that includes the overcast have been computed, as noted, using the nominal cross-sections and nominal velocities. The values thus obtained are of interest chiefly in calling attention to the effects produced by these obstructions, and for comparison with values of k for unobstructed entry.

FIG. 17. APPROACH TO OVERCAST BETWEEN SECTIONS C_4 AND C

the regulator. With a quantity of 9840 cu. ft. per min. (traverse 4E), this represents an energy loss of 0.032 h.p. This is equivalent to the losses of about 3000 ft. of straight entry at a mean velocity approximating that in these panel entries.

Static section E_4 was established opposite section E in the return airway for the current flowing through E. The static pressure drop of 0.066 in. was observed independent of a specific traverse, so the quantity of air flowing is uncertain. (The areas of E and E_4 are substantially the same, so that the total pressure loss is the static pressure drop.) Furthermore, since this drop includes that due to the regulator it should be reduced by 0.020 in. leaving a net value of 0.046 in., representing the losses through the panel proper. However, if an estimated value of 9800 cu. ft per min. be accepted as the quantity (traverse 4E gave 9840 cu. ft. per min.) the pressure drop noted is equivalent to 0.07 h.p. lost in ventilating the working panel involved (3rd and 4th SE.).

26. *Losses Due to a Split.*—Energy losses at the split just below section C (Fig. 11) were studied in connection with a series of velocity-pressure traverses taken at C, D, and E in immediate succession. The respective quantities were 17 810, 8720, and 9840 cu. ft. per min., the two partial quantities totaling substantially more than the main quantity. The error was thought to be largely in the determinations at D and E due to the difficulty of making accurate determinations at such low

velocities (see p. 42) so these two quantities were arbitrarily adjusted to 8360 and 9450 cu. ft. per min., respectively, to bring their sum equal to the main quantity. On this basis the total energy at C was 0.066 h.p. greater than the combined energies at D and E.

An interesting phenomenon in connection with differential static pressures was noted here. Ordinarily the static pressure decreases as one goes downstream, but this may not be the case at a split, the reverse being true in going from C to D and from C to E. Bernouilli's theorem relating to the flow of fluids states that the total pressure from cross-section to cross-section remains the same, save for energy losses, provided no external work is done on the system. However, the total pressure is made up of two parts, static pressure and velocity pressure, either one of which may be increased or decreased at the expense of the other by changing the cross-section of the duct. This is essentially what happens at a split. The cross-section is so increased that the mean velocity of the current as a whole falls appreciably, and hence its velocity pressure is notably decreased. The total pressure may suffer but a slight decrease, the reduced velocity pressure being augmented by an increased static pressure. The increases observed from C to D and C to E were small but qualitatively definite, being 0.0019 and 0.0013 in. of water, respectively.

VI. Flow of Air in Mine Airways

27. Criteria for Flow of Air.—More than forty years ago Osborne Reynolds in a paper* read before the Royal Society gave results of his researches on the flow of water in tubes. His experiments showed that there are two types of motion, steady and turbulent. He demonstrated these types of flow by means of a stream of colored water introduced into a glass tube through which water could be drawn at various velocities, and showed that at a definite velocity of the water the steady motion changed to turbulent flow. He proposed a formula for this critical velocity based on the diameter of the pipe and on the density and viscosity of the fluid.

The investigations of Dr. T. E. Stanton at the National Physical Laboratory using air as well as water have confirmed Reynolds' criterion and have shown that for velocities greater than $V = \frac{2500\,\nu\dagger}{d}$ the flow is turbulent, and for velocities less than this critical value the flow is

*Phil. Trans. Royal Soc., 1883.

†V is velocity in ft. per sec., d diameter of pipe in ft., ν the coefficient of kinematic viscosity in ft. lb. sec. units. ν is about 0.00016 for air at 65° F.

steady. The application of this formula to mining conditions shows* that in every case where there is a flow of air that might be dignified by the name of a "ventilating current" the flow is turbulent and not stream-line.

28. *Atkinson Formula.*—In 1854 J. J. Atkinson read a paper† giving the results of his measurements of mine resistance. The formula commonly used for mine ventilation calculations is the one which he developed, $R = ksv^2$, where R is the total resistance of the mine in pounds, s the "rubbing surface" (length of airway multiplied by perimeter) in square feet, and v the velocity in feet per minute. The "coefficient of friction," k, was a proportionality factor determined experimentally, and the Atkinson coefficient, 0.0 000 000 217, is still the most commonly used value for k, although known to be too high.

Atkinson's assumption that the resistance to flow varied as the square of the velocity has not been substantiated by the researches of Stanton and his assistants, for the exponent of V has been shown to lie between about 1.65 and 2, but is not constant, being a function of $\frac{Vd}{\nu}$ and also of the relative roughness of the surface of the passageway. Since almost no experimental investigations have been carried on to compare the flow of air in mines with Stanton's results in pipes it seems unwise at the present time to attempt to assign a fractional exponent for V. Values for k have been calculated, therefore, on the assumption‡ that the mine resistance varies directly with the rubbing surface and the square of the velocity.

It should be pointed out, however, that k must not be considered merely as a simple coefficient of friction, but as a factor covering all energy losses of whatever nature, whether losses that might be classed as friction losses due to the rubbing of air on the sides of the airway, or to air layer rubbing on air layer, or losses due to the effects of either ordinary or extraordinary turbulence. High values of k cannot be explained on a simple frictional basis alone, but a physical conception of turbulence will aid in grasping the reason for large energy losses.

The irregularities of mine airways are, of course, conducive to turbulence in the air stream. These irregularities are present in many forms, in the pitted surfaces of the ribs, and to a less extent of the roof, in the roughness of the floor due largely to the presence of debris, in

*For a circular entry 8 ft. in diameter the critical velocity is 3 ft. per min.; 4 ft. in diameter, 6 ft. per min.

†On the Theory of the Ventilation of Mines, Trans. North of England Inst. Min. Eng., v. 3, pp. 73-222.

‡On this assumption it is evident that k cannot be a constant, but will vary as some function of the velocity. The extent of this variation was not determined in this work as it was not possible to vary the velocity.

sinuousity of the ribs, variations in cross-sectional area, and changes in grade and elevation of the roof and floor.

The cross-sectional area and perimeter are affected by the presence or absence of timbers, and signally so by the presence of cross-cuts. This is illustrated in Fig. 4, which shows a portion of the Main East air course in plan and graphs of its area and perimeter. Both of these curves show a striking similarity to the plan of the rib from which the cross-cuts were driven, because, the height remaining constant both area and perimeter become more nearly direct functions of the width as the width increases. In computing the factor k in this work the increase in area and perimeter due to cross-cuts was ignored on the assumption that the air flow would be stream-lined past them in a channel approximately continuous with the effective channel in the entry proper.

29. *Observations with Ammonium Chloride Fumes.*—The actual behavior of the air in passing cross-cuts was observed by discharging a cloud of ammonium chloride fumes into the air current and noting its course along the entry. These white fumes were generated by blowing a small current of air through a bottle containing a strong aqueous solution of ammonium hydroxide and passing the resulting vapor-laden current through a bottle of hydrochloric acid. A dense white cloud of ammonium chloride resulted, which could be directed into the aircurrent as desired, and whose production could be maintained for appreciable lengths of time. For a diagram of the generating apparatus see Fig. 18.

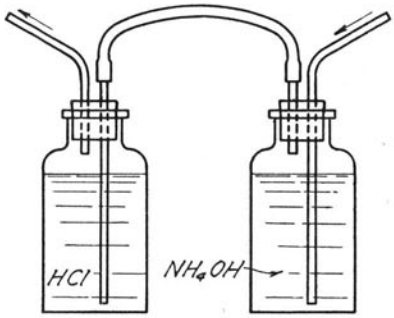


FIG. 18. AMMONIUM CHLORIDE GENERATING APPARATUS

As the cloud came to a cross-cut it split into two portions just above the downstream corner of the cross-cut, the major portion continuing along the entry, and the smaller portion entering the cross-cut. This followed the downstream side of the cross-cut to the stopping, thence along the stopping to the upstream side of the cross-cut and along it to rejoin the main current once more. This definite eddy with smaller, less constant ones was the characteristic feature noted in a number of these observations; in some cases a greater, in others a lesser portion of the main current being directed into the cross-cut. No estimation can be given of the proportion of the main current which is deflected into the cross-cut to re-enter the main current again, but it is relatively small.

At the split below C, Fig. 11, the air seemed to be quite well-coursed, some eddying being noticeable in the recess in the right-hand rib just upstream rom the 4th South entry. As might be expected, the velocity on the left (east) side of the 4th South just beyond the split was appreciably greater than that on the opposite side, probably due to the fact that the actual splitting was effected by the nearby rib corner. A similar condition was noted in that portion of the current continuing in the Main East entry, in that the velocity on the right (south) side just beyond the split was greater than that on the opposite side. This may be due to the slight deflection of the entry to the left where the 4th South was turned off.

The dust troughs seemed to cause little or no extra turbulence, the air being whisked rapidly and smoothly between them. A little eddying was noticed about the regulator but less than might be expected at such a marked obstruction.

A similar absence of marked turbulence was noted at the overcast. In spite of the abrupt changes in cross-section and elevation of the passageway, the air seemed to be moving in smooth stream lines. It swept rapidly into abrupt expansions and wherever motion was apparent it seemed to be dominantly progressive.

The entry plans, drawn as they are to a large scale, give an impression of smoothness which may more nearly express the conditions affecting the general flow of the air than the actual non-uniform nature of the walls of the entry would indicate. This is borne out in the general lack of extraordinary turbulence noted in the ammonium chloride observations.

While the high resistances offered by such obstructions as dust troughs, overcasts, etc., equivalent to the resistance of hundreds of feet of unobstructed entry, are due primarily to increased turbulence, yet this extraordinary turbulence seems to be difficult to render visible, the tendency being for the ammonium chloride fumes to be picked up by the more direct-moving currents rather than by the small swirls and eddies.

A cause of loss that should be mentioned specifically lies in the contraction and expansion of the air stream due to changes in cross-sectional area. While ideally this would not occasion loss due to the mutual convertibility between static head and velocity head, this convertibility is not perfect and any contraction or expansion of the air stream is accompanied by an energy loss. Such changes are obviously characteristic of flow through an irregular passageway such as a mine airway.

30. *Flow of Air as Shown by Isovel Diagrams.*—Defining an isovel as a line connecting points of equal velocity in a given cross-section, isovel diagrams were drawn for a number of individual traverses at several traverse sections. Under ideal conditions, with the highest velocity at the center of the section and decreasing in all directions away from the center with the minimum at the outlines, the isovels would form a series of closed concentric curves, closely following the outlines of the section near the periphery, and more nearly approaching circularity toward the center.

Three diagrams of this general type are shown in Fig. 19 (traverses 4C, 13F, 12G). Having no detailed knowledge of conditions nearer the edge of the section than the outermost traverse points the lines were not drawn beyond these limits, their exact behavior being a matter of conjecture. It is evident from the asymmetrical distortion of each of these diagrams that conditions of air flow were not geometrically ideal in any of these traverses. This shifting of the velocity distribution is probably due to irregularities in the immediate approach to or departure from the traverse section, and to curvature in the course of the entry as a whole, which might shift the major flow of the air to one side or the other

This condition is well illustrated in Fig. 20 (traverse 3D) which shows the maximum velocity to be well toward the right-hand rib. It will be recalled (Fig. 11) that section D is just beyond a split to the south and a deflection in the course of the entry which would be expected to produce the effect noticed. The vertical stratification of air velocities to the left of the maximum velocity zone is interesting.

Section E is but 6 ft. upstream from the regulator previously described (p. 57) and is also only a short distance from the split at the Main East. The effect is a very distorted and varying velocity distribution as shown in Fig. 21 (traverses 3E, 4E). The difference between the two diagrams illustrates the difficulty in obtaining check quantities in successive traverses, the results in these two traverses differing by 13 per cent from their mean. Neither diagram shows the effect of the regulator opening so close below the traverse section, the conditions of approach seemingly having been the determining factor in the air distribution, rather than those of departure.

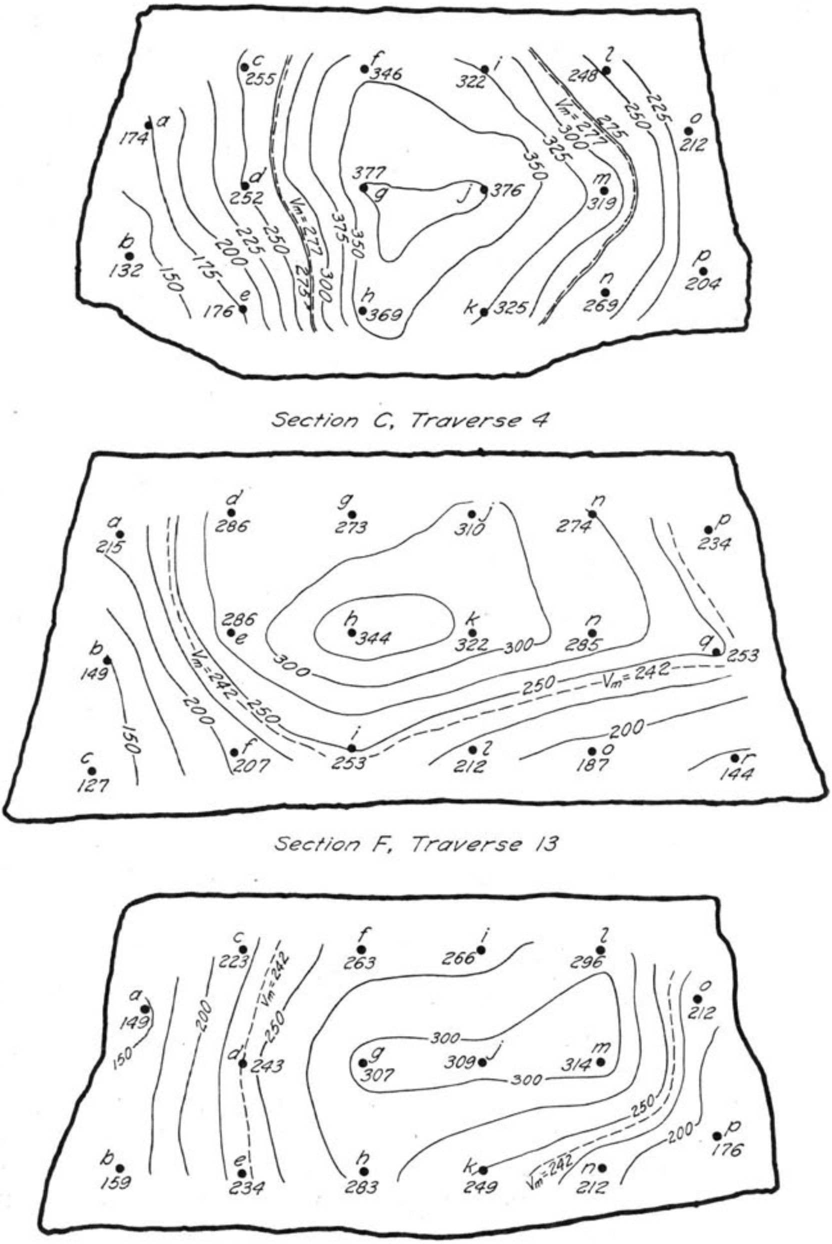


FIG. 19. ISOVEL DIAGRAMS FOR SECTION C—TRAVERSE 4, SECTION F—TRAVERSE 13, AND SECTION G—TRAVERSE 12

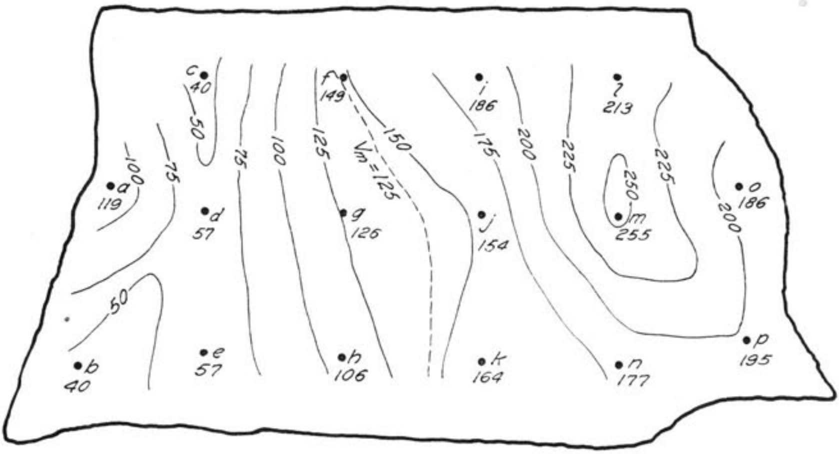


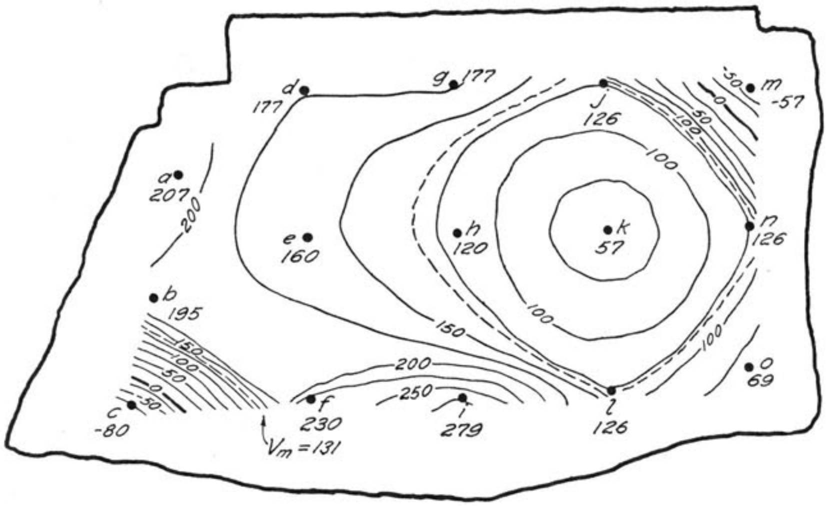
FIG. 20. ISOVEL DIAGRAM FOR SECTION D—TRAVERSE 3

At section A, Fig. 9, there are two centers of high velocity approximately on the horizontal centerline giving a lemniscatic shape to the isovels surrounding them. They actually represent the division of one large high velocity zone into two smaller ones by a vertical zone of relatively low velocity. The cause of these consistently low velocities in this central zone is not apparent. The area is well removed from the rib, and the roof and floor presented no irregularities which could be expected to give rise to such a condition. Furthermore, the center line of the entry is essentially straight for a considerable distance (a few hundred feet) either way from the section, thus excluding the explanation of curvature. That some definite influence is upsetting the normal distribution of the air is further indicated by the vertical attitude of the isovels in the right-hand portion of the section. It may be that a curvature of the entry, so slight as to have escaped notice, has brought this about.

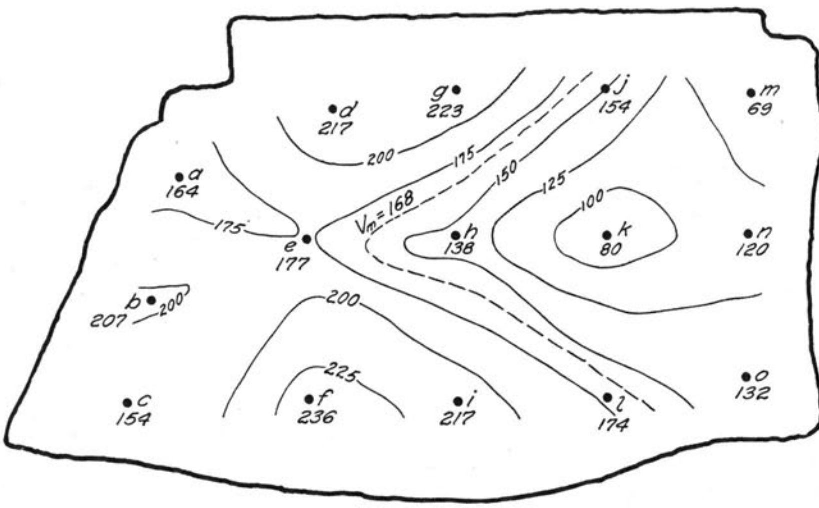
While the 12-subsection isovels from traverse 15A (Fig. 9) are based on too few points to give the total effect of the other diagrams they show some of the essential features characteristic of the others, e.g., the close, vertical parallelism at the right, and the low velocity area to the left of the center.

Another feature of the unequal velocity distribution is that the quantity flowing to the left of the vertical center line is about 15 per cent in excess of that flowing to the right, as shown by the average results calculated for traverses 8, 15, and 16.

If the isovels could be drawn accurately to the boundary of the cross-section they would afford a more accurate means of measuring



Section E, Traverse 3



Section E, Traverse 4

FIG. 21. ISOVEL DIAGRAMS FOR SECTION E—TRAVERSES 3 AND 4

quantities by determining the areas between successive lines, than by assuming the velocity at a given point to prevail throughout a certain area. To get a comparison between the two methods the quantity flowing within an area bounded by a line joining the outermost subsection points was determined both by the planimeter and by calculation for traverses 16A and 12G. The results were not conclusive, however, as difficulty was experienced in getting an exact check on the areas with the planimeter, due to the smallness of the scale used in plotting the isovel diagrams. This may indicate that the actual accuracy to be procured by this method is no greater than by the method used, due to unavoidable errors in drawing the isovels, and in measuring the areas with a planimeter.

A significant feature noticed in this work, however, was that a very large percentage of the cross-sectional area lies without the line joining the outermost traverse points, and that nearly as large a percentage of the total quantity is considered as flowing through this area by the method of computation used in this work.

However, the error involved in attributing the velocity at the various outer traverse points to the marginal areas adjacent to each may not be as large as might be expected. This is indicated by the fact that the air at the ribs, roof, and floor seemed to be moving substantially as fast as that a foot or so away, as judged by ammonium chloride observations. Furthermore, it is apparent that errors, probably equally as great, may be involved in attributing the velocity at a given point well within the section to a substantial area around that point. The marked inequalities in the distribution of velocities, are illustrated by most, if not by all, of the isovel diagrams.

A comparison between the quantity obtained in a 16-subsection traverse at section A and what would have been obtained in the same traverse with 20 and with 12 subsections respectively, was obtained by superimposing the 20- and 12-subsectional diagrams on the 16-subsection isovel drawing and taking the velocities to be attributed to the 20- and 12 subsectional points by interpolation from the isovels between which they fell. This assumes that the isovel drawings accurately represent the conditions of air flow, and that there would be no error in field work had actual velocity-pressures been determined instead of interpolating the velocities from the drawings. There is error in both of these assumptions, but they furnish an interesting basis for comparison. Of the four traverses studied in this way (6, 8, 13, 17 at A) the 20- and 12-point subsection quantities were always lower than the 16- subsection (standard) quantities, by less than 2 per cent, however, and the 12-subsection lower than the 20-subsection by about 1 per cent.

Since the velocity drops more rapidly near the outlines of the section than elsewhere the greater the number of points the closer the outer ones approach this low-velocity zone, with a resulting lowered total quantity. Thus the 12-subsection quantity should be greater than either the 16- or 20-subsection quantities instead of less. The explanation for this discrepancy will be apparent on an examination of the 12-subsection diagram (Fig. 6). None of the points are at the central high velocities, whereas this is not true of either of the other two subdivisions. Had the 12-subsection diagram been geometrically similar to either of the other two, it would undoubtedly have yielded a higher quantity.

31. *Variations in Quantities and Resistances.*—The inconstancy of the conditions of air flow underground has already been mentioned. Variations in quantities, pressures, and lines of flow are characteristic, and to be expected from the physical nature of the conditions involved. The probability of substantial quantity variation has been suggested in connection with the traversing at section A. In an attempt to get at the cause of this condition the behavior of the fan was observed from time to time during some subsequent work. For the most part it was quite steady in its speed at 135 r.p m., but occasionally it would vary irregularly for a few minutes, for the most part dropping below the normal value, the speed falling to 127 r.p.m. in one extreme instance. However, the range was usually within 3 or 4 per cent of the normal value. The cause of the fluctuation is uncertain but is probably due to irregularities in electrical conditions on the lines of the public service company. They have no relation to hoisting or other local loads, however, so far as could be determined. From day to day, and certainly for the major part of the time, the speed was steady at its normal value, but whether or not this was true during the traversing at Section A cannot be said. Even if the fan speed remained constant there would be many opportunities for quantity changes in a given entry in the mine, due to the varying resistances offered by moving trips, opening and closing of doors, adjustment o' regulators, etc.

The effect of such changes on pressures is shown graphically in Fig. 22 in which the static pressure drop in the 1st and 2nd South panel ($G_3 - G_2$) and in its return airway ($G_1 - G_2$), with the center-velocity pressure at G, are plotted against time with notations concerning the behavior of trips, and the opening and closing of doors. (Fig. 23 shows a plan of the panel and the points referred to on the graph.)

It is clear that such changes in physical conditions produce marked effects on the air currents, as is to be expected. It is interesting to note

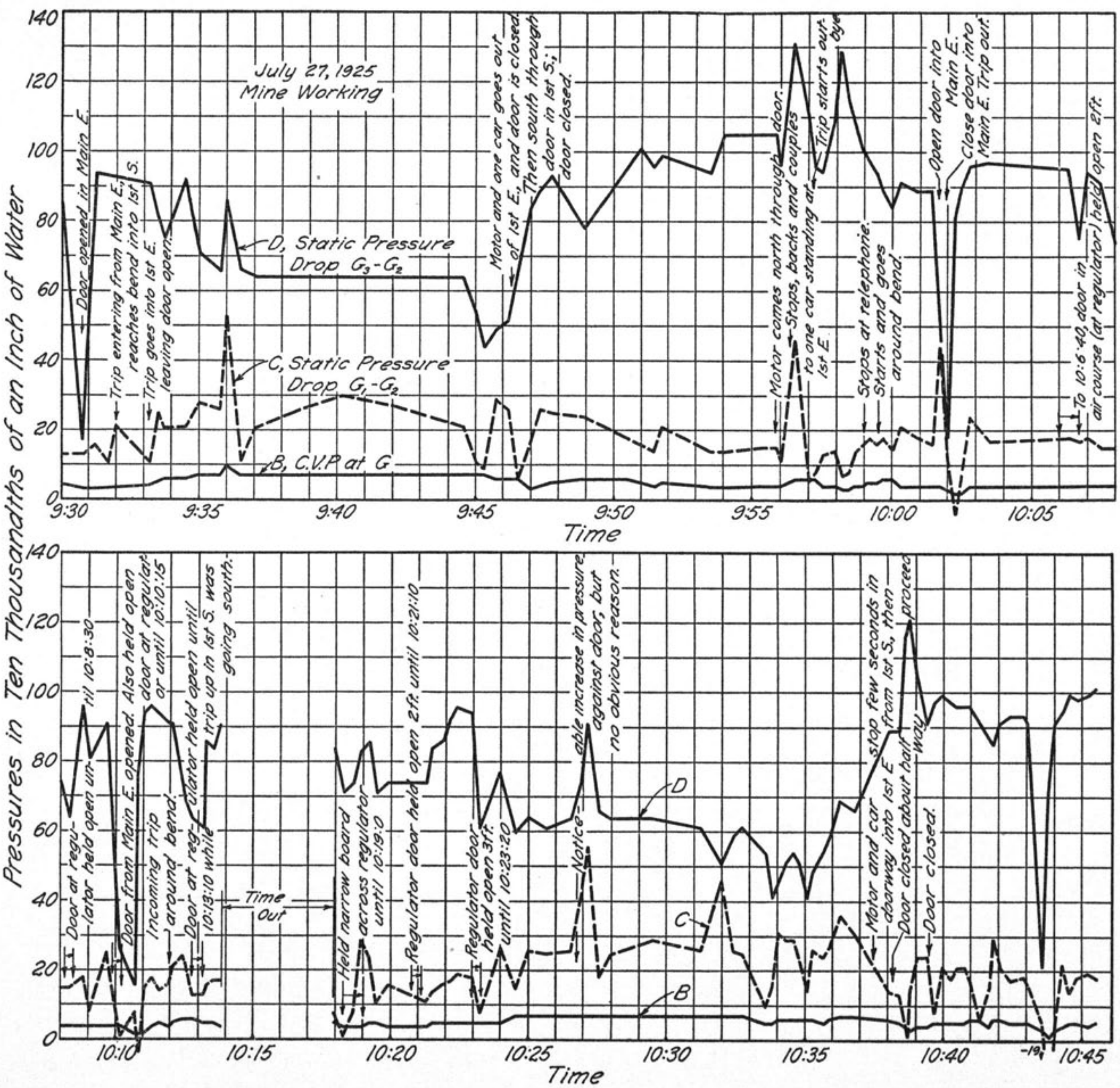


Fig. 22. Fluctuations in Static Pressure Drop and Center-Velocity Pressure at Section G

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that while door 3 between the 1st and 2nd South at the 1st East was left open (9:35 to 9:46), thus short-circuiting the air without sending it throughout the working panel, the resistance of the panel as a whole dropped substantially from about 0.09 in. to less than 0.07 in. while the center-velocity pressure rose from 0.04 to 0.07 in. and the static pressure drop from $G_1 - G_2$ rose from 0.02 to 0.03 in. due to the increased quantity resulting from the decreased panel resistance. As a loaded trip returned on the 1st East it evidently blocked the air entirely, or virtually so, for a moment (9:45) as it crossed the 2nd South. After the trip had cleared this entry the air flow was resumed and the static pressure drop in both test units rose again, continuing to its normal horizon. However, when door 3 was closed (9:46) the immediate supply of air through $G_1 - G_2$ was cut off, to be gradually restored as the air completed the circuit of the panel. This is reflected in the curve of static pressure drop, $G_1 - G_2$ in the drop from 9:46 to 9:47. A lowered center-velocity pressure is also evidenced at this time.

The slight depression in both static pressure drop curves at 9:56 is of interest and is probably due to the instantaneous blocking of almost the entire cross-sectional area of the intake air course (1st South) as the trip passed through the door frame. The unusually high pressures immediately following this may have been something of a "rebound" effect as the air was suddenly released when the trip cleared the door. Another depression occurs in both curves when the trip starts out "against the air," followed by numerous irregularities in all three curves, impossible of individual interpretation, as the trip proceeds. The trips pass from the Main East aircourse to the Main East haulage road through door 1, Fig. 23. There is a large static pressure differential between these two entries, and the opening of the door constitutes an effectual short-circuit of the air flow, as evidenced by the precipitous drop in the static pressure curves at 10:02, 10:11 and 10:44.

The sharp increase in the static pressure drop ($G_1 - G_2$) just before its drop at 10:02 is probably an "accidental" effect in so far as apparent causes go, although it is possible that the sudden opening into a low-pressure zone at door 1 permits an actual reversal of the air flow in the Main East aircourse and 1st South. Since there is a regulator at door 2 an air reversal would affect G_3 and G_1 simultaneously, reducing both their absolute and differential pressures. At the instant of release at G_1, however, G_2, 600 ft. farther inbye on the 2nd South would be as yet unaffected and at a much higher pressure with respect to G_1 than normally. This may be expressed in the peak before the valley in this curve at 10:02 and 10:09. It is not apparent in the third instance at 10:44.

The depressions in the resistance curves at 10:06, 10:08, 10:13, etc. were intentionally induced by the observers by opening door 2, Fig. 23, which is adjacent to a regulator. They represent normal drops due to short-circuiting part of the air past the panel. The effect of the reverse operation, that of blocking off part of the opening of the adjacent regulator is not clearly shown by the graphs, partly because it was done so soon after gage readings were resumed that the previous behavior of the curves is in doubt although it was apparently erratic. However, the pressure rose sharply while the obstruction was in place and this is consistent with what would be expected, although this rise cannot be clearly identified as coming from this source.

From time to time during the day a sudden increased swish of air rushing through the regulator could be heard. One of these was recorded on the gages at 10:27. The cause could not be determined but was probably some sudden removal of resistance such as the opening of a door farther inbye. No explanation is at hand for the marked fluctuations from 10:31 to 10:36 but they are probably connected with the movement of trips, as is the case for the remainder of the curve.

VII. Summary of Conclusions

32. *Conclusions.*—(1) It is possible to measure air quantities in coal-mine airways by pitot-tube traversing methods and to obtain check results that are reasonably accurate when it is remembered that the quantity of air flowing in a mine airway is a varying quantity, being affected by a number of mine activities.

(2) Satisfactory results can be obtained only when extreme care is used in every detail of the work.

(3) While check results can be secured by anemometer traversing yet the values thus obtained are much higher than the true quantities. It seems improbable that anemometer determination can be relied on unless the anemometer is calibrated under the exact conditions of use.

(4) Rapid cross-sectioning to obtain areas and perimeters is possible by using a modified plane table equipment. This method is just as rapid as and more satisfactory than the offset method.

(5) The value of k for different conditions of normal entries varied from 0.0 000 000 046, for a stretch of straight, clean air course with smooth roof and floor and only occasional props to 0.0 000 000 095 for a straight air course with sinuous, irregular

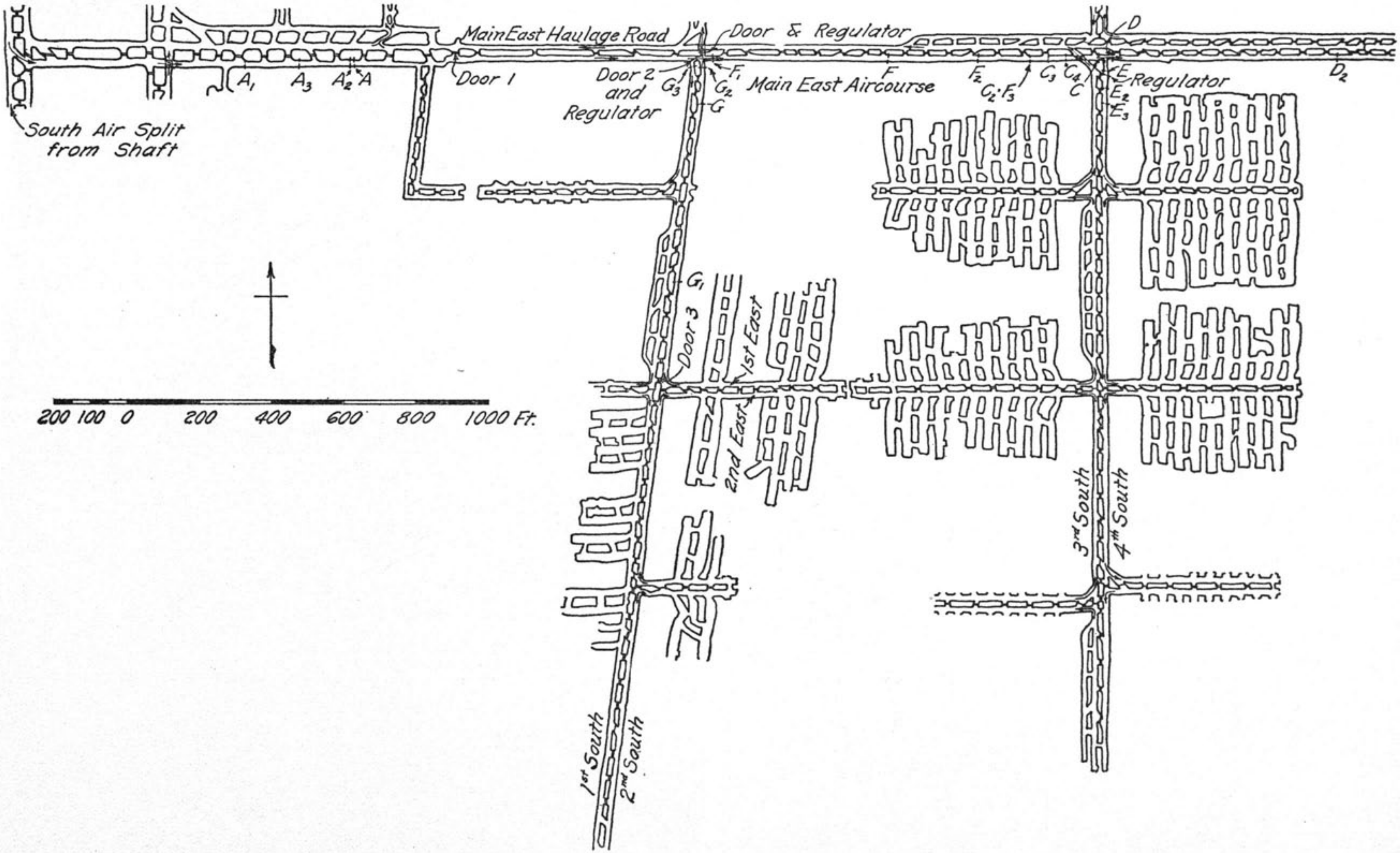

FIG. 23. PORTION OF MINE MAP SHOWING LOCATION OF SECTIONS AND DETAILS OF VENTILATION

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ribs, little timber, and with much debris on the floor. For a straight, clean haulage entry with smooth roof and ribs k was 0.0 000 000 051.

(6) The great resistance caused by the type of rock-dust barrier illustrated in Fig. 14 is shown in the high value of k for such an entry—0.0 000 000 420.

(7) The high factor, k = 0.0 000 000 320, for a short stretch of entry that included the overcast shown in Figs. 11 and 16 reflects the irregularities and extreme roughness of this section and the losses due to changes in direction of the air current.

(8) Losses for an entire panel or for a considerable length of entry are less than would be shown by a simple calculation based on the length involved. This is true for two reasons: first, due to leakage through the stoppings the full quantity of air does not travel the entire distance; and second, in a panel with rooms the air does not travel a single path but divides and travels in numerous currents, idling through the panel at a very low velocity.

The first case is well illustrated by panel $G_3 - G_2$. The total pressure loss for 600 ft. of panel entry was 0.020 in., while the loss for the entire panel, about 7000 ft. of entry, was only 0.106 in. instead of 0.234* as might have been expected. Inasmuch as this panel had practically no rooms it is evident that most of the difference between the actual and expected losses can be attributed to leakage through stoppings and doors reducing the quantity of air in circulation.

The second case is illustrated by panel $E - E_4$, where a total pressure loss of only 0.046 in. resulted for a panel entry distance of 10 200 ft. whereas if the full quantity had traveled this distance, instead of drifting through the rooms and leaking through stoppings, a drop of about 0.167† might have been expected, nearly four times the actual loss.

(9) Isovels constructed from traverse observations show a very distorted velocity distribution. This irregularity is evident even in sections that might be supposed to have uniform air flow.

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*$0.020 \times \frac{7000}{600} = 0.234$.

†The quantity of air flowing through E is only 0.7 of the quantity in G. The size and condition of the entries in each panel are about the same so that the expected loss $= 0.020 \times (0.7)^2 \times \frac{10\,200}{600} = 0.167$ in.

(10) The effect of the disturbances on ventilation produced by the normal operating activities of the mine is very marked. Not only are there appreciable changes in quantity but the pressure losses show great fluctuations due to the changes in the circulation of the air caused by opening and closing of doors and by trips of cars obstructing the entries.

Appendix A. Explanation of Tables Summarizing Ventilation Data

I. Net Velocity-Pressure Readings.—Table 2.

Column 1. (Subs.) Subsection. This gives the letter by which the individual subsections into which a traverse section was subdivided are designated The pitot tube was placed in the center of each subsection and the derived velocity for that setting is attributed to the entire area of the subsection.

Column 2. (Max.) This column gives the maximum net velocity-pressure obtained during each pitot setting.

Column 3. (Min.) Similarly, this column gives the minimum net pressure.

Column 4. (Mean). The mean value which was used in computing velocity is here given.

Column 5. (Extr. % Var.). Extreme per cent Variation. This shows for a given traverse and subsection the amount by which the reading farthest from the mean differs from it, expressed as a percentage of that mean.

II. Pitot Traverse Data.—Tables 5-8.

Column 1. Traverse No. gives the serial number assigned to the traverse in the field, the numbers running upward from 1 for each section. There are some gaps because some traverses were abandoned before being completed in the field, e.g. Tr. 3A and 5F. Some traverses are repeated on consecutive lines because they were computed by two different methods; one in which all of the readings taken were used in computing Q (designated as "All" under "Remarks"); the other in which only the more consistent readings were used (designated as "Selective" under "Remarks").

Column 2. (Date). The field work was done during the summer of 1925.

Column 3. (I.-R.). Idle or Running tells whether or not the mine was idle or operating.

Column 4. (Subs). Number of subsections. The method of subdivision was varied in Sec. A only.

Column 5. (Gage). "E" indicates use of Ellison gage, "W" Wahlen.

Column 6. (Op.). Operator. "H" is for traverses in which gage was read by Prof. Hoskin, "S" for those in which it was read by Mr. Smith.

Column 7. (V_c). Center Velocity. The average air velocity is here given in feet per minute at the center of the section as determined by center velocity-pressure readings on the Ellison gage; not taken in every instance.

Column 8. (V_m). Mean Velocity. This column gives the average air velocity in feet per minute through the cross-section in question at each traverse, derived by dividing the total quantity (Q. Col. 11) by the area of the section.

Column 9. $\frac{(V_m)}{(V_c)}$. This is ratio of the mean velocity to the center velocity. Desirable as a "center-velocity constant" if a consistent value could be established.

Column 10. (% Var.). The variation of each individual ratio, $\frac{V_m}{V_c}$, from the mean of all the ratios for any one section is expressed as a percentage of that mean.

Column 11. (Q). Quantity. The quantity of air in cubic feet per minute, flowing through the cross-section, as determined from velocity-pressure readings.

Column 12. (% Var. from Mean). Opposite each traverse is set the amount by which that quantity varies from the mean of all the quantities, expressed as a percentage of that mean, as in Column 10, previously described, "+" indicating that the quantity in question is greater than the mean, "−" that it is less. No account is taken of sign in averaging the columns.

Column 13. (Q_m). Mean Quantity. The averages of selected groups of quantities. The average of all the quantities at one section is found at the foot of the quantity column (No. 11 Q). In the mean quantity column "I" stands for the average of all quantities determined on idle days; "R" of those on running, or working days; "S" the average of traverses taken by Mr. Smith; "H", of those taken by Prof. Hoskin; "E", of those taken with Ellison gage; "W", of those taken with Wahlen gage. These traverse characteristics are combined to give more restricted groups, such as the average of quantities determined on idle days by Prof. Hoskin; designated by "IH".

Column 14. (Remarks). "V" for velocity; "ind" for index of the Wahlen gage. In a number of traverses with this gage a series of readings was taken at each pitot setting until a number of them, about four or five, agreed within certain limits. It was planned to use only the closely-agreeing readings, discarding all others. These results are marked "Selective" in this column to distinguish them from the quantities obtained from the same traverse data, using all the velocity-pressure readings recorded. In the earlier work with the gage the meniscus was brought to index position under velocity pressure only once for each pitot setting. These are designated "Single setting." Later the number of settings was increased as noted in number of readings taken. In other cases only a single setting was made but instead of bringing the meniscus to the index position, with the gage under velocity pressure, its behavior was watched for a short time and its position averaged so that it was presumably as much above the index line as below it. This is called "Average meniscus" in this column.

III. Anemometer Traverse Data.—Table 9.

Column 1. (Pitot Tr.). Gives the serial number of the pitot traverse immediately preceding which the anemometer traverses listed opposite it were taken.

Column 2. (Op.). Same as Column 6, Part II.

Column 3. (Anem. Vel.). Gives air velocity in feet per minute at the stated section, as determined by successive anemometer traverses, usually three in immediate succession.

Column 4. (Mean Anem. Vel.). Gives the average of the individual anemometer traverse results for each pitot traverse.

Column 5. (% Var.). Gives the amount by which each individual traverse under Column 3 varies from the mean of its group under Column 4, expressed as a percentage of the mean listed in Column 4, "+" indicating that the individual traverse is greater than the mean, "−" that it is less.

Column 6. (Mean % Var.) is to Column 5 what Column 4 is to Column 3.

Column 7. (Pitot Vel.). The air velocity in feet per minute as determined by the pitot traverse, using the Ellison gage.

Column 8. $\frac{V_p}{V_a}$. Gives the ratio of the velocity as determined by pitot traverse to that determined by anemometer traverses.

Column 9. (% Var.). Amount by which individual ratio $\frac{V_p}{V_a}$ varies from mean of all ratios.

PUBLICATIONS OF THE ILLINOIS COAL MINING INVESTIGATIONS

Bulletin **1.** Preliminary Report on Organization and Method of Investigations. **1913.** *None available.*

Bulletin **2.** Coal Mining Practice in District VIII (Danville), by S. O. Andros. **1913.** *None available.*

Bulletin **3.** Chemical Study of Illinois Coals, by S. W. Parr. **1916.** *None available.*

Bulletin **4.** Coal Mining Practice in District VII (Mines in bed 6 in Bond, Clinton, Christian, Macoupin, Madison, Marion, Montgomery, Moultrie, Perry, Randolph, St. Clair, Sangamon, Shelby and Washington counties), by S. O. Andros, **1914.** *None available.*

Bulletin **5.** Coal Mining Practice in District I (Longwall), by S. O. Andros. **1914.** *None available.*

Bulletin **6.** Coal Mining Practice in District V (Mines in bed 5 in Saline and Gallatin counties), by S. O. Andros. **1914.** *Free upon request.*

Bulletin **7.** Coal Mining Practice in District II (Mines in bed 2 in Jackson County), by S. O. Andros. **1914.** *Free upon request.*

Bulletin **8.** Coal Mining Practice in District VI (Mines in bed 6 in Franklin, Jackson, Perry and Williamson counties), by S. O. Andros. **1914.** *Free upon request.*

Bulletin **9.** Coal Mining Practice in District III (Mines in beds 1 and 2 in Brown, Calhoun, Cass, Fulton, Greene, Hancock, Henry, Jersey, Knox, McDonough, Mercer, Morgan, Rock Island, Schuyler, Scott, and Warren counties), by S. O. Andros. **1915.** *Free upon request.*

Bulletin **10.** Coal resources of District I (Longwall), by G. H. Cady. **1915.** *None available.*

Bulletin **11.** Coal Resources of District VII (Counties listed in Bulletin 4), by Fred H. Kay. 1915. *Twenty-five cents.*

Bulletin **12.** Coal Mining Practice in District IV (Mines in bed 5 in Cass, DeWitt, Fulton, Knox, Logan, Macon, Mason, McLean, Menard, Peoria, Sangamon, Schuyler, Tazewell, and Woodford counties), by S. O. Andros. **1915.** *Free upon request.*

Bulletin **13.** Coal Mining in Illinois, by S. O. Andros. **1915.** *Free upon request.*

Bulletin **14.** Coal Resources of District VIII (Danville), by Fred H. Kay and K. D. White. 1915. *Twenty-five cents.*

Bulletin **15.** Coal Resources of District VI, by G. H. Cady. **1916.** *Fifteen cents.*

Bulletin **16.** Coal Resources of District II, by G. H. Cady. **1917.** *Fifteen cents.*

Bulletin **17.** Surface Subsidence in Illinois Resulting from Coal Mining, by L. E. Young. **1916.** *Fifteen cents.*

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